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FAKULTA STROJNÍHO INŽENÝRSTVÍ

INSTITUTE OF MANUFACTURING TECHNOLOGY

ÚSTAV STROJÍRENSKÉ TECHNOLOGIE

PRODUCTION OF THREADS WITH FORMING TAPS

VÝROBY ZÁVITŮ TVÁŘECÍMI ZÁVITNÍKY

MASTER'S THESIS

DIPLOMOVÁ PRÁCE

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BRNO UNIVERSITY OF TECHNOLOGY FACULTY OF MECHANICAL ENGINEERING

Master's Thesis Assignment

Institut:	Institute of Manufacturing Technology
Student:	**Bc. Yegor Yermakov**
Degree programm:	Mechanical Engineering
Branch:	Manufacturing Technology and Management in Industry
Supervisor:	**prof. Ing. Miroslav Píška, CSc.**
Academic year:	2016/17

As provided for by the Act No. 111/98 Coll. on higher education institutions and the BUT Study and Examination Regulations, the director of the Institute hereby assigns the following topic of Master's Thesis:

Production of threads with forming taps

Brief description:

On the base of a theoretical analysis of the technology for production of threads the experimental work will follow with a final assessment of the technological and economic parameters, achieved quality and further optimization of the production.

Master's Thesis goals:

1. Theoretical analysis of material forming during use of forming and cutting taps.
2. Analysis of specific forming forces at manufacture of the threads, compared with símilar results for cutting taps.
3. Design experiments and their implementation.
4. Analysis of results, discussion.

Recommended bibliography:

FROMENTIN, G., POULACHON, A., MOISAN, B., JULIEN, J., GIESSLER AGAPIOU, J.S., Precision and surface integrity of threads obtained by form tapping. CIRP Annals - Manufacturing Technology, Volume 54, Issue 1, 2005, Pages 519-522.

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Students are required to submit the thesis within the deadlines stated in the schedule of the academic year 2016/17.

In Brno, 6. 11. 2016

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FME dean

ABSTRACT

This diploma thesis deals with issues in production of threads. Its first part describes kinds of taps used in mechanical engineering. Then it focuses on issues about fundamental principles of threading and material forming during machining. Later on it focuses on comparing of forming and cutting taps forces during the treatment. The diploma thesis also describes an experiment of torque measurement by using forming tap. All the measured values were statistically processed and conclusions were then evaluated. The final part is devoted to a calculation of production costs.

Key words

threads, forming taps

ABSTRAKT

Tato diplomová práce se zabývá otázkami výroby závitů tvářecími a řezacímí závitníky. Její první část popisuje druhy závitníků, které se používají ve strojírenství. Pak se práce zaměřuje na otázky základních principů řezání závitů a tváření materiálu při obrábění. Dále se zaměřuje na porovnání řezných momentů a dalších veličin při aplikaci tvářecích závitníků v procesu obrábění. Výsledkem experimentu bylo zjíštění průběhů řezných momentů v závislosti na čase, který byly statisticky zpracovány a vyhodnoceny.

Klíčová slova

závity, tvářecí závitníky

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DECLARATION

I declare that the master thesis on the topic **Production of threads with forming taps** worked out by my own by using of professional literature and sources referred to the list that create an attachement of this work.

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Datum Bc. Yegor Yermakov

GRATITUDE

I would like to thank prof. Ing. Miroslav Píška, CSs., for essential comments and advices during the elaboration of the master thesis, and Jiří Čech from Department of Machining Technology VUT for help in experiment.

CONTENT

INTRODUCTION

The first usage of helical surfaces in the technique goes back into ancient times. It is believed, that the first screw was invented by Archytas (Greek: Ἀρχύτας; 428–347 BC), philosopher, a mathematician and engineer, who lived in IV—V centuries BC. Widely known, the Archimedes screw, shown in Fig. 1, is used for transferring water from a low-lying body of water into irrigation ditches. Water is pumped by turning a screw-shaped surface inside a pipe. The first fasteners having a thread started to be used in Ancient Rome in the beginning of AD. However, due to the high cost they were only used in jewelry, medical instruments and other expensive products [27].

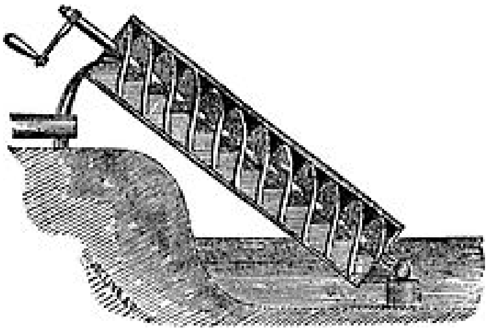


Fig. 1. The Archimedes screw [12].

Broad usage of threads found in the middle Ages. Prodaction of external thread took place as follows: a cylindrical rod was wraped by smeared cord with chalk or paint, then a spiral groove was cut through spiral-formed markup. Bushings with two or three pins were used instead of nuts with internal thread.

Production of triangular and tetrahedral taps for internal threading was started in XV—XVI centuries. Both connecting parts with external and internal thread for screwing were fitted to each other manually. Any interchangeability of parts was completely absent.

Background to the interchangeability and standardization of threads was created by Henry Maudslay, about 1800, when he invented a screw cutting lathe, that made possible the accurate cutting of threads, Fig. 2. Feed screw and nut for his first machine were made by hand. Then he turned the screw and nut on the machine with a higher accuracy [13].

Fig. 2. Henry Maudslay [13].

Fig. 3. Sir Joseph Whitworth [14].

Replacing the first screws and nuts by new ones, which were more accurate, he was able to turn more precise details. Cycle continued up until the thread accuracy had not suspended to increase.

Over the next 40 years, the interchangeability and standardization of threads took place only within the individual companies. In 1841 Joseph Whitworth, Fig. 3, developed a system of mounting threads, which was accepted by many English railway companies, and then became a national standard for the United Kingdom, called British Standard Whitworth (BSW). The Standard served as the basis for the creation of different national standards. For example, standard Sellers in USA, threads of Loewenherz (Deutsch: Löwenherz) in Germany, etc. [14]

In 1947 was founded the international organization for standardization (ISO). The thread standards ISO are currently accepted and used worldwide, Fig. 4.

Fig. 4. ISO logo [15].

Threaded connections are actively used not only in mechanical engineering, but in such significant for humans branches as, for example, medicine, civil or electrical engineering. For present days, in my opinion, there are two main problems for threads producing: to make it quick and with high quality.

Simultaneously, to reduce machining time and improve the product quality, it is necessary to explore thoroughly the technological parameters of cutting tools and the processes occurring during the treatment. Nowadays, threading internal threads by taps is the most widespread method of threaded holes making.

This diploma work will describe comparison of forming and cutting taps.

1 BASICS IN THREADS

Threads represent significant constructional and technological elements of mechanical engineering parts, that perform different connecting or moving functions. Thread is a helical groove of a particular profile, which is cut on cylindrical or conical surfaces. Threads can be produced by cutting, grinding, rolling, stamping, casting and using electrophysical or electrochemical treatment. The most common and versatile method of producing threads is cutting machining. From a technological point of view cutting of threads is distinguished to internal and external. Internal and external threads may be machined by taps and dies (hand or machine), turning or milling operations. Threads may also be produced by grinding and by various forming operations [1, 2, 5].

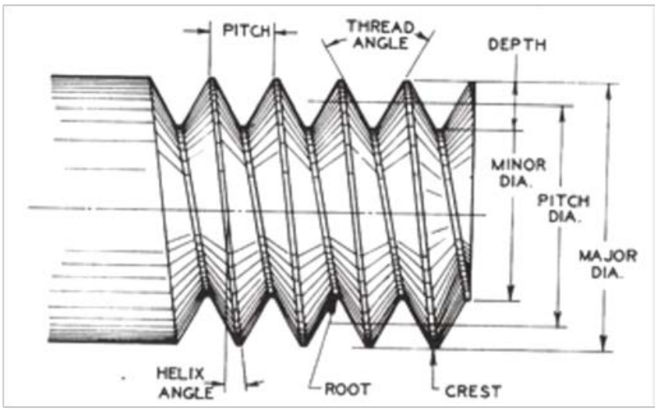


Fig. 5. Screw thread nomenclature [9].

Definitions of thread parameters, shown in Fig. 5 [9] :

1) Pitch. The shortest axial distance between two corresponding points of adjacent crest of the thread.
2) Pitch diameter. This is the diameter of an imaginary cylinder, passing through the threads at the points where the thread depth is equal to the space between threads.
3) Major (nominal) diameter. This is the largest diameter of a screw thread, touching the crests on an external thread or the roots of an internal thread.
4) Minor (core) diameter This is the smallest diameter of a screw thread, touching the roots or core of an external thread (root or core diameter) or the crests of an internal thread.
5) Lead. It is the distance a screw advances axially in one turn.
6) Crest. The top surface connecting the adjacent flanks at the top of the thread.
7) Helix Angle. The angle made by the helix, or conical spiral. Of the thread at the pitch diameter with a plane perpendicular to the axis.
8) Thread angle. This is the angle included between the flanks of the thread, measured in an axial plane.
9) Root. The bottom surface joining the two sides of the thread.

Theoretical profile of the thread for screw and nut are similar, but basic profiles are different (Fig. 6) [8].

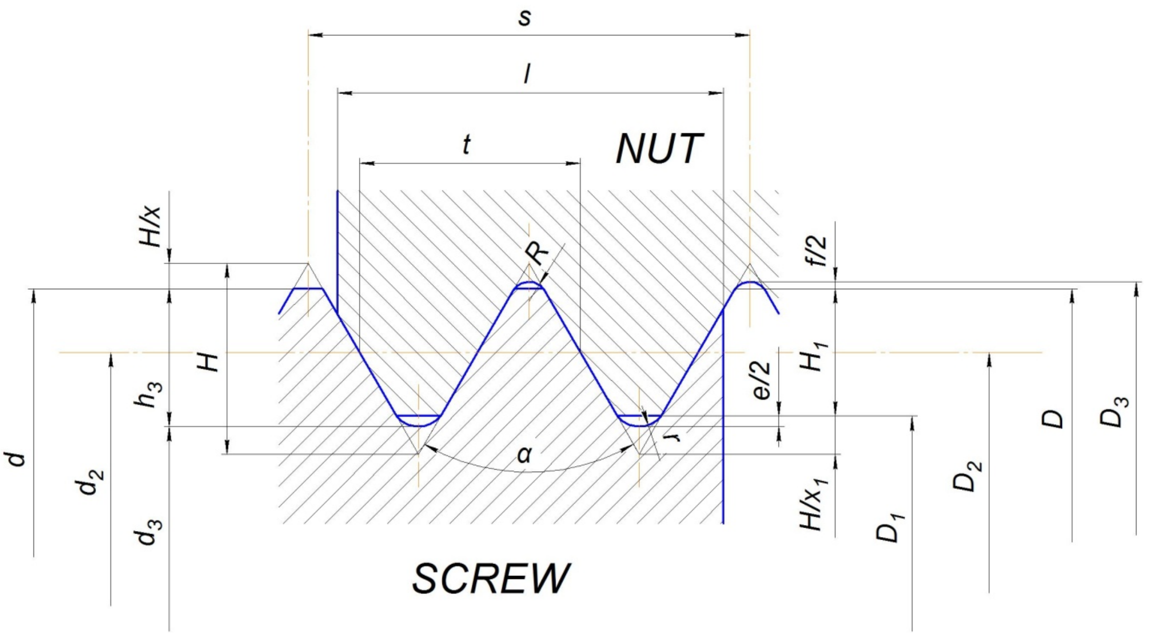


Fig. 6 Basic parameters of the thread [8].

d − major diameter of external thread

D − major diameter of internal thread

D_1 − minor diameter of internal thread

$d_2 = D_2$ − pitch diameter

d_3 − minor diameter of external thread, $d_3 = d - 2h_3$

D_3 − bottom diameter of internal thread

h_3 − depth of the screw's thread, $h_3 = H\left(1 - \frac{1}{x} - \frac{1}{x_2}\right)$

H − theoretical depth of the thread

H_1 − primary depth of internal thread, $H_1 = \frac{d - D_1}{2}$

H/x − outermost height of external thread

H/x_1 − innermost height of external thread

r − bottom radius of groove of external thread

R − bottom radius of groove of internal thread

l − screwing length

α − thread angle

e − innermost clearance of external thread, $e = D_1 - d_3$

f − outermost clearance of external thread

Threads may perform different functions, and can be divided into several groups:

1) Placement – internal and external,
2) Purpose – fastening and moving,
3) Surface – cylindrical and tapered
4) Handedness – left-hand and right-hand
5) Profile – triangular, square, trapezoidal and circular
6) Start – single-start and multiple-start.

Fastening threads usually have isosceles triangular form, designed for connecting machine parts. Moving threads designed for transforming rotary motion into linear motion. Tapered threads ensure high tightness and therefore can be used under high pressure of liquids and gases. The helical groove of right-hand thread has clockwise direction, and may be identified by right hand grip rule. Threads oriented in the opposite direction are known as left-handed. If the thread has one helical groove on its surface, this thread is single-start. Multiple-start means the thread has multiple helical grooves.

To ensure that the two (internal and external) halves of a threaded joint fit together properly to produce a connection capable of withstanding a specified load, threads must maintain certain standards. International standards for thread forms have therefore been established for all common thread types. According to ISO metric thread designation, the complete thread designation is made up of values for the thread form and the tolerance. The tolerance is indicated by a number for the tolerance grade, and letters for the tolerance position. Example of thread designation [22]:

$$M10\text{x}1{,}25\ 5g6g$$

where M – kind of thread (metric in this case)

10 – nominal diameter of thread, [mm]

1,25 – pitch, [mm]

5g – tolerance class for pitch diameter

6g – tolerance class for crest diameter.

1.1 Tolerance grades of internal and external thread

It is known, that actual profiles of nut and bolt threads must never cross the theoretical profile, otherwise produced thread will not be able to function due to jamming. Practically, to make a thread, tolerances must be applied to provide this essential principle.

The method of applying manufacturing tolerances to the female and male threads such that they fit together by use of the tolerance class which is a combination of the tolerance grade (a number) and a tolerance position (a letter). For the female threads the letter is upper class and for the male threads the letter is lower class. The tolerance band positions relative to the basic zero size are illustrated in the Fig. 7 [18].

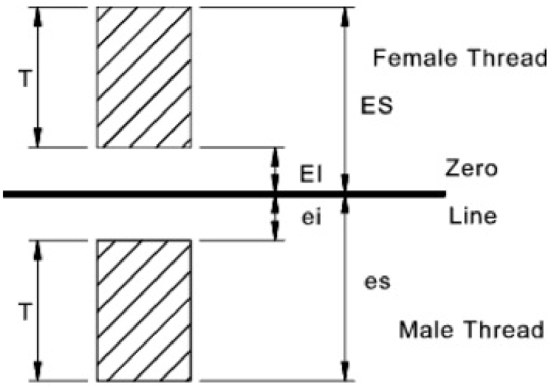


Fig. 7. Tolerances for external (male) and internal (female) thread [18].

The tolerance position is defined as the nearest end of the tolerance band to the zero tolerance position. These positions are identified as *EI* for the female thread and *es* for the male thread. There are a limited number of tolerance grades used to specify threads and the standards identify these grades for the Minor (D_1) and Pitch (D_2) diameters of the female threads and the Major (d) and Pitch (d_2) diameters of the male threads. Tolerance grades are not provided for none critical female major diameter (D) and the male minor diameter (d_3). The numbers of grades used are listed below:

D_1 : tolerance grades 4, 5, 6, 7 and 8,

d : tolerance grades 4, 6 and 8,

D_2 : tolerance grades 4, 5, 6, 7 and 8,

d_2 : tolerance grades 3, 4, 5, 6, 8 and 9.

To simplify the selection of the tolerance classes, demonstrated in Fig. 8, threads have been divided into three categories. “Fine” for precision threads, “Medium” for general industrial usage and “Coarse” for rough manufactured threads. The length of thread engagement is also used as a parameter for selection of the tolerance class. The following Table 1 identifies the range of tolerance classes and the length of screws for selecting the length parameter. Available tolerance positions are:

EI: G and H for female threads,

es: e, f, g and h for male threads.

Table 1. Thread tolerances [18].

Female Threads						
Class	Tolerance Position G			Tolerance Position H		
	Short	Normal	Long	Short	Normal	Long
Fine	-	-	-	4H	5H	6H
Medium	5G	6G	7G	5H	6H	7H
Rough	-	7G	8G	-	7H	8H

Male Threads												
Class	Tolerance Position e			Tolerance Position f			Tolerance Position g			Tolerance Position h		
	S	N	L	S	N	L	S	N	L	S	N	L
Fine	-	-	-	-	-	-	-	4g	5g4g	3h4h	4h	5h4h
Medium	-	6e	7e6e	-	6f	-	5g6g	6g	7g6g	5h6h	6h	7h6h
Rough	-	8e	9e8e	-	-	-	-	8g	9g8g	-	-	-

It should be noted, that if two shaft tolerance grades are shown the first is for the pitch diameter and the second is for the major diameter. When only one is shown it is the same for both diameters [18].

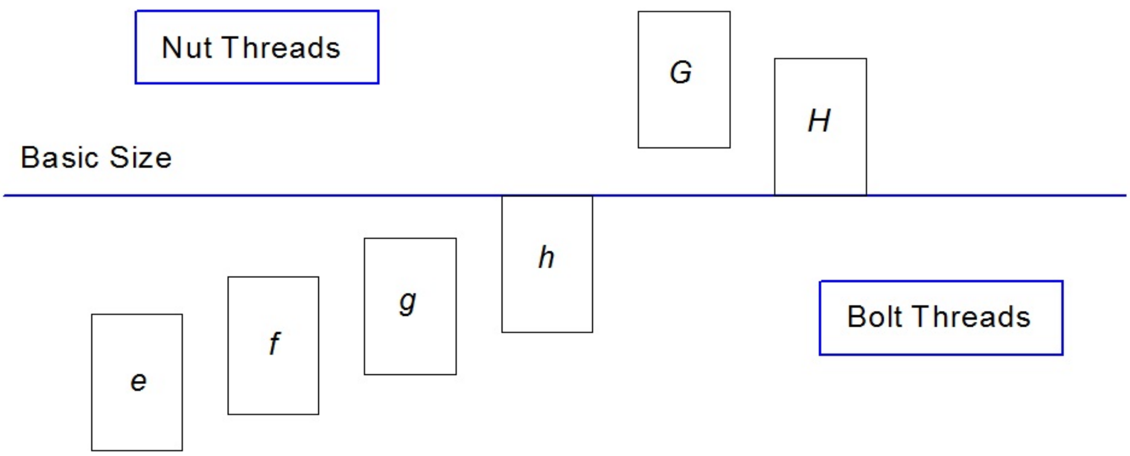


Fig. 8. Tolerance classes.

2 KINDS OF TAPS APPLYING IN MECHANICAL ENGINEERING

In mechanical engineering taps are used for manufacturing of internal threads, moreover, taps can be applied without machine, i.e. by hands. The material of the tap usually is high-speed steel or cemented carbides, in both ways it may be coated by different abrasion resistant materials, such as TiC, AlTiN, TiSiN for improving mechanical features [19, 20].

A tap is a rotary tool for making internal threads, with similar geometry to a screw. The size and geometry style are the two major considerations in selecting the correct tap for a particular material and machine part setup. The tap style is defined by the number of flutes, rake or hook angle, chamfer length, land and helix angle [5].

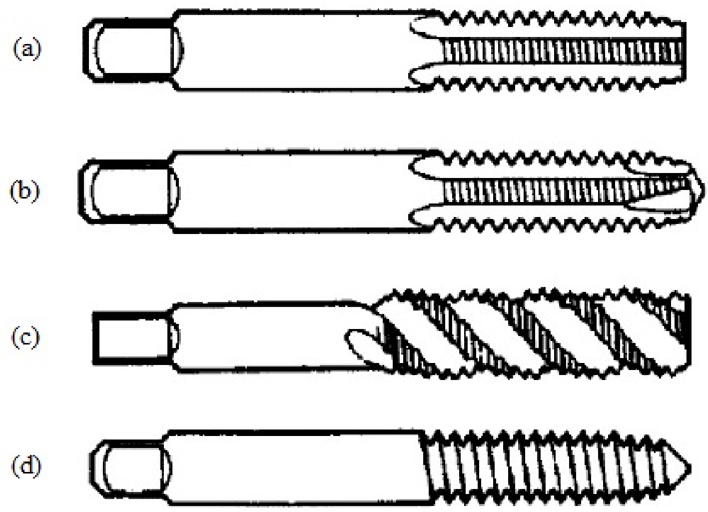


Fig. 9 Sorts of taps [5].

a) straight flute bottoming style, b) spiral pointed plug style, c) spiral flute bottoming style, d) roll form plug style.

Typical tap is a rod, which has shank on the one end and the thread on another end, as it demonstrated in Fig. 10. A cutting tap has series of single point cutting edges arranged linearly and radially on the tool periphery as it shown in Fig. 9.

In tapping of internal threads, a specially formed threading tool is fed into a hole drilled in a previous operation. The tap may either cut or plastically deform the hole wall material to form the thread [5].

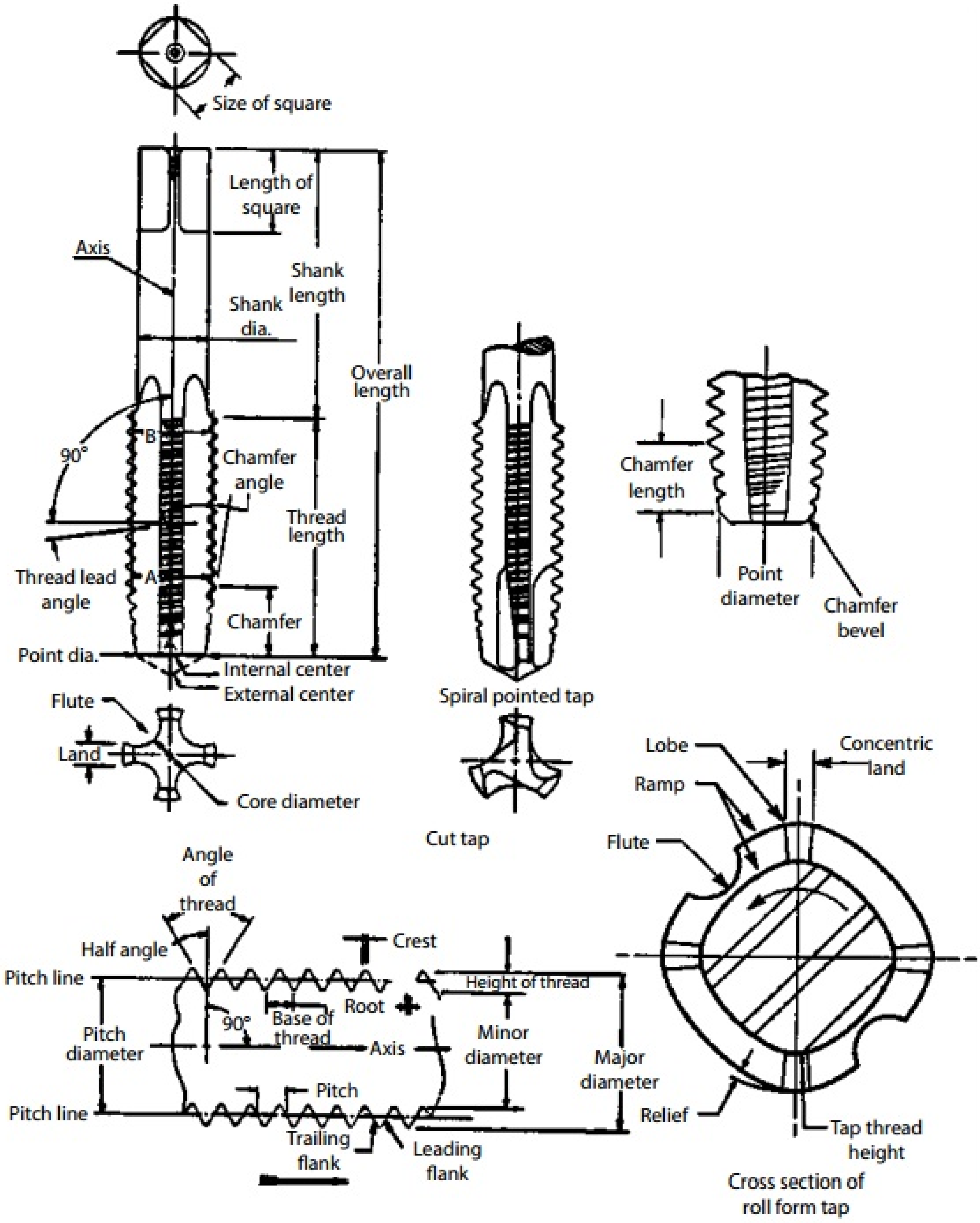


Fig. 10. Nomenclature of cutting and forming taps [5].

Cut and roll form taps, shown in Fig. 10, are the major tap styles used for internal threading. Cutting taps cut and remove material to produce the thread; roll form taps displace or plastically deform metal to form the thread profile.

2.1 Forming taps

Featuring unique geometric designs, coatings, and styles, forming taps provide an efficient solution for the chipless production of internal threads in a wide range of applications. Their polygon shape and various forming wedges are specifically designed to produce the effective thread profile for the unique properties of the workpiece material. As a result, taps are able to form threads that in some situations cannot be efficiently machined with cutting taps. Different tap designs are available to thread seven different material groups including regular steel, soft steels, hardened steels, wrought aluminum alloys and non-ferrous metals, cast aluminum, stainless steels and materials with restricted ductile properties [3, 4].

Forming taps create thread by displacement of material within the hole. Roll form taps, which produce threads by deformation, can be used in ductile materials such as free-machining steels, soft carbon and alloy steels, austenitic stainless steels, and ductile aluminum, copper, zinc, and magnesium alloys. The formed material assumes the shape of the thread form of the tap without the creation of chips. These taps are fluteless except as optionally designed with one or more lubrication grooves. The thread form is lobed, so there is a finite number of points contacting in the work. Other features of the cutting tap, like chamfer, are altered to direct the forces required to cause the material being threaded to assume a new form. Tap lands separated by flutes are replaced by high areas called lobes, shown in Fig. 10 and Fig.11. These lobes are relieved to reduce surface contact with the work material. Friction reduction is a major objective in successfully forming threads. They are also a likely solution to the challenges of tapping blind holes: as forming taps produce no chips, there are no issues with chip interference and removal [4, 5].

Fig. 11. Forming taps [3].

Roll taps produce no chips, but require consistent lubrication and control of the pre-tapped hole diameter to prevent excessive tapping torque and tap breakage. Roll-form tapping can produce stronger threads with work-hardening materials (steels and stainless steels). The most common machines used for tapping are drilling machines, milling machines, and lathes [2, 5].

Tapping is used for through holes and blind holes. Drilled through holes can be tapped along the entire length. Blind holes are tapped to a specified length and sometimes called bottom holes. Blind hole tapping requires accurate depth control to avoid ramming the tap into the bottom of the hole, causing tool failure, or an insufficient number of threads. Bottoming taps must pull chips up and out of the hole, as compared to through-hole taps, which usually push chips out of the hole in front of the cutting edge.

Forming taps require a slightly larger hole, as the material being threaded flows into, as well as away from, the threads of the tap. The finished minor diameter of the hole will be smaller than the unthreaded hole when the process is complete. It should also be mentioned, that forming taps run better at speeds 1-1/2 to 2 times faster than a cutting taps, and require much more attention to lubrication of the tool, as friction between the tap and the workpiece can create problems with generated heat and torque forces imposed on the entire set-up [5].

2.2 Cutting taps

Historically, internal threads were created by cutting taps. These are tools that are designed to remove the material from the hole leaving a finished internal thread form in the geometry intended. These tools, that are shown on Fig. 12, utilize a feature, known as the chamfer, to achieve a gradual cutting action as the tap enters the hole, and flutes to allow remove the chips created by this cutting action, and provide coolant or lubricant to assist in the process of cutting [4].

Fig. 12 Cutting taps [7].

Roll and cut tapping produce different thread profiles as shown in Fig. 13. In cut tapping, the minor diameter of the thread is determined by the diameter of the existing hole. The metal removal rate is governed by the tap’s effective chamfer length, number of flutes, and rpm in addition to the minor diameter [5].

Cutting taps are more versatile, as the geometry of the tool can be altered to match the characteristics of the material being tapped. They could be applied for any material to machine, and application of forming taps is limitted. Materials like cast iron and phenolic plastics, which are not candidates for forming, can be addressed with a cutting tap. Cutting taps may be a better choice for through holes as they won't require a separate operation to repair the distortion at entry and exit caused by the forming tap. Cutting taps require less machine power than a forming tap, a major consideration as tap diameter increases.

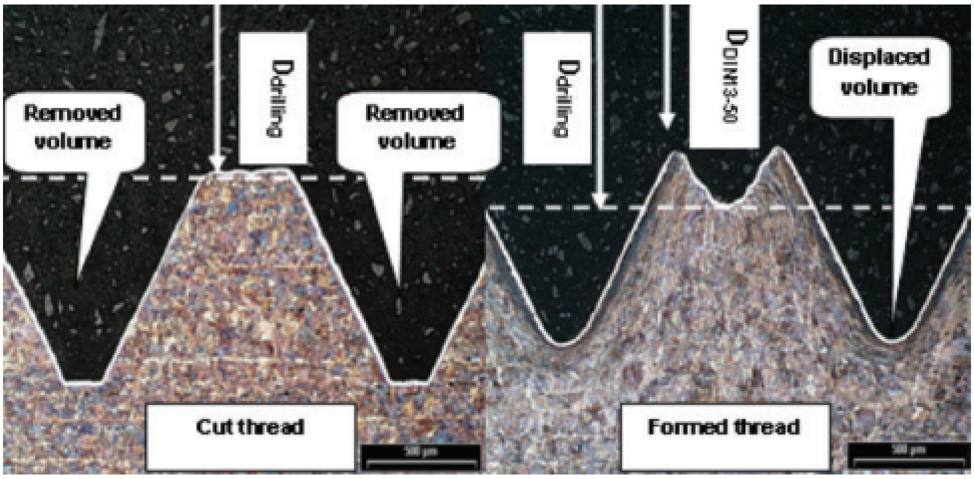


Fig. 13 Micrographs of cut and formed threads [6].

2.3 The influence of the preparatory diameter

If the preparatory diameter is too small the workpiece material is overformed in the thread root and there are excessive process forces. If the preparatory diameter is too large the thread root is not sufficiently formed, the minor diameter is too small. In order to prevent such negative effects, the tolerance of cold-forming taps is narrowed down from the start. In some cases where the forming characteristics are very extraordinary it may be necessary to go without a standard preparatory diameter entirely, and to find the correct diameter by testing. It is important to know that the preparatory diameter has a significant influence on the minor diameter of the nut thread. Every lack of precision, every kind of surface roughness will be mirrored in the finished internal thread and its minor diameter [24].

2.4 The influence of chamfer length

As it mentioned at article [5], the chamfered teeth and the tap's first full thread cut or deform the material. Each succeeding chamfered tooth makes a deeper cut until the full thread is generated. The chamfer has a direct relationship to the chip load as it shown in Fig. 14 and Fig. 15.

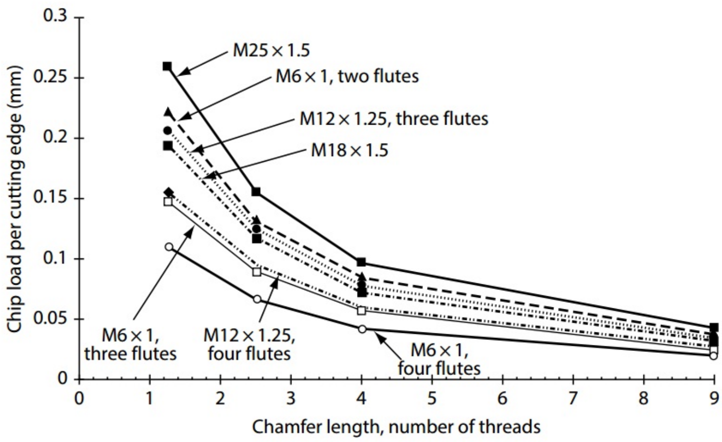


Fig. 14. The effect of chamfer length on chip removal [5].

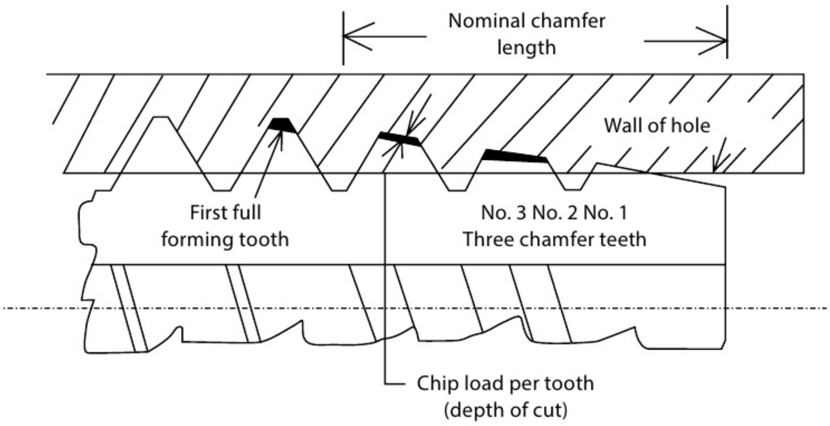


Fig. 15. Chip load of the tap [5].

Therefore, it is important to use the proper chamfer depending on the thread pitch, workpiece material, percentage of thread and type of the hole. Commonly used chamfers include taper, plug and bottoming, which are illustrated in Fig. 16. Chamfer of the tap is designed for materials, which are difficult to machine, because it provides better distribution of chip load per tooth, resulting in better thread quality. The chamfer should not exceed 3–5 threads for taps used in hardening materials such as alloys and stainless steels, so as to produce chips that are thick enough to allow the cutting edges to undercut any previously work hardened surface. The plug chamfer, with an average chip load per tooth, is usually used for through holes in most materials. The bottoming chamfer results in a large chip load over its few cutting teeth, which requires less torque, and is used mainly for blind holes. The longest chamfer should be used to improve tap's efficiency, accuracy of dimensions and tool life, even though a long chamfer increases the cycle time and requires a deeper drilled hole. Titanium alloys often require longer chamfers to prevent galling on the chamfer relief surfaces. The geometry of the transition from the chamfer to the tap's full diameter also affects tap performance [5].

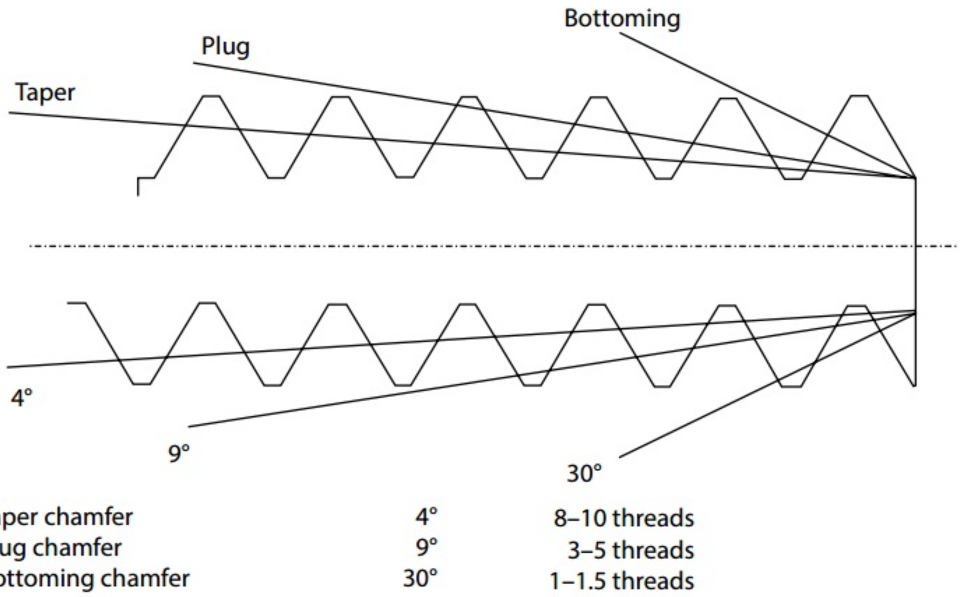
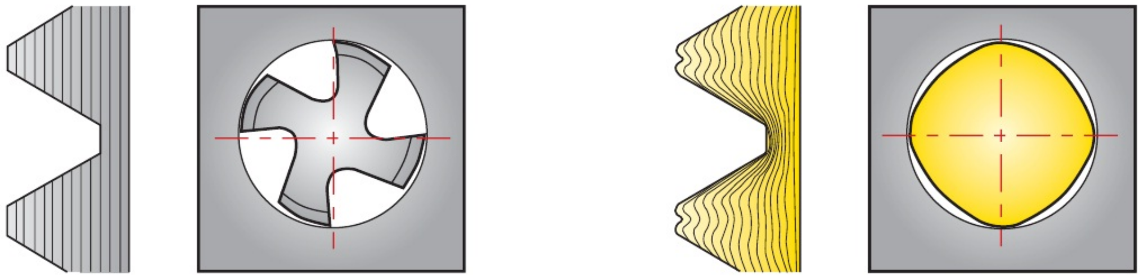


Fig. 16. Influence of chamfer on geometry of the tap [5].

3 THEORETICAL ANALYSIS OF MATERIAL FORMING DURING USE OF FORMING AND CUTTING TAPS

With a cut thread, the permissible values of stress are limited due to the fact that the grain structure of the material is cut. Also, flank angle errors can occur easily; these will cause a very unfavourable distribution of stress on the thread and limit its holding strength. With a cold-formed thread, the grain of the material is not cut or interrupted, and the material itself shows increased strength, due to its having been compressed by cold-forming. Flank angle errors which are quite common in cut threads are prevented by the material being formed. The incomplete minor diameter, typical for cold-formed threads, has no influence on the stripping resistance of the thread. Cold forming causes material strengthening on the thread flanks and especially in the root area of the thread. This strengthening of the material structure has a very positive influence on the vibration properties and the general resistance of the thread under dynamic stress [23, 24].



a b

Fig. 17. Profile of the thread manufactured by [16],

a) cutting tap, b) forming tap.

As it is shown in Fig. 17, it is obviously, that formed threads are stronger than cut threads. When threads are formed, the grains of the material is compressed, particularly at the root and crest of the manufactured thread form. While a cut material's grain structure has been fractured by the cutting action of the tool.

The cold forming of threads, according to DIN 8583-5, belongs to the pressure-forming processes. The internal thread is manufactured by the impression of a helical sequence of thread teeth into the formerly prepared thread hole, the desired profile is formed by pressure. According to the property that metal will occur plastic deformation and flow under pressure, internal thread will form in the lead hole under the extrusion effect of extrusion tap. As it is shown in Fig. 18, the lead hole, which diameter is approximately equal to the pitch-diameter of internal thread is machined in the workpiece firstly, then the extrusion tap, which teeth size are consistent with the require teeth size of internal thread is used to tapping at a certain feed speed, then the ridges and lobes of tap teeth will extrude into the surface layer of metal, and the root of internal thread will form gradually, the extruded metal will flow along radial direction, heighten and form the full teeth gradually [23, 24].

Due to the cross-section of extrusion tap is polygon, not a whole circle, every moment only part of teeth will extrude material, leading to periodic pressure on metal, the change frequency is proportional to the edge number of extrusion tap and rotational speed, under the periodic pressure, metal occurs plastic deformation and forms internal thread. The formation of the thread is obtained by the successive action of the lobes of a tap. Each lobe causes a three-dimensional plastic flow. This plastic flow leads to an important strain hardening of the work material (an increase close to 100 % of the initial hardness), which induces the tap wear [6].

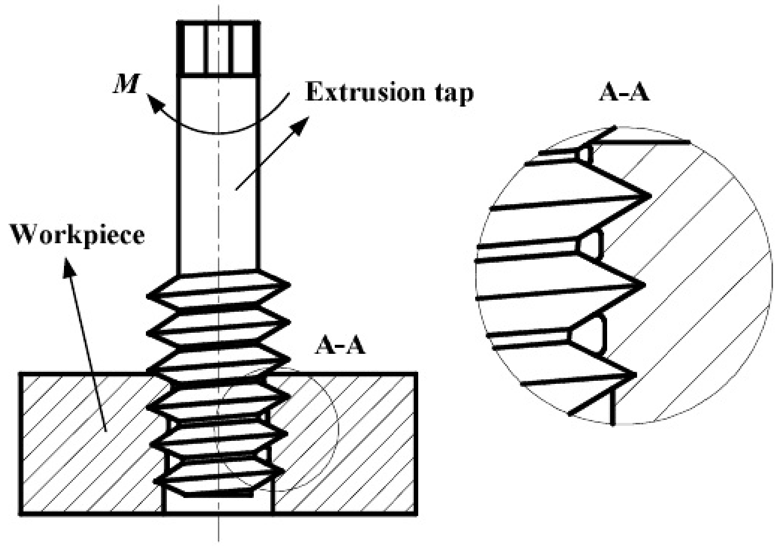


Fig. 18. Extrusion tapping of internal thread [23].

3.1 Thread forming process and metal plastic flow law during extrusion tapping

The usage of form tapping leads to plastic flow of the work material when making the thread. No metallurgical transformation is observed, nevertheless this process necessarily involves a strain hardening of the material constituting the thread [28].

In metal plastic deformation one part of crystal change its position regarding other part under tangential stresses. When the load is removed and displacement of crystals in metal remaining plastic deformation occurs.

Thread obtained by form tapping undergoes a high strain hardening and there is a strongly deformed layer at the thread surface. This deformed layer is largely influenced by the intensity of the friction between the thread former and the work material. As a consequence, the lubricant has a prime importance on thread characteristics. The strain hardening would raise the strength of the thread. The drawback is that this hardening has necessarily an effect on wear of the form tap, which would be considerably reduced by using an efficient lubricant.

Based on the model set up in article [23], the simulation of extrusion tapping was conducted by the linear scratch. Fig. 19 shows the development of thread forming process with the scratch 0, 3, 10 and 15, and the split crest is obvious after scratch 15.

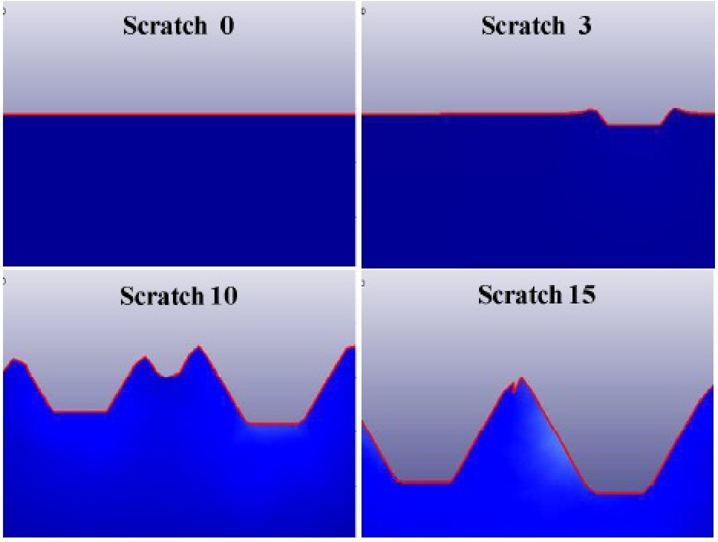


Fig. 19. Thread forming process during extrusion tapping [23].

According to the feature of metal plastic deformation, the metal flow occurs in the direction with the smallest resistance during tap forming process. Whereas the geometry of forming tap's crest consist of groove on the top, which has the direction of curvature to the center of the tap (tap track in scratch 10, Fig. 19), it can be assumed, that the metal plastic flow rate along thread flanks is higher than that in the center of the thread.

In the article [23] thread is divided into five regions with the different metallurgical characteristic, Fig. 20. The zone (Z1), core of the material of lead hole, does not undergo any deformation. The zone (Z2) shows the root of internal thread which is in contact with the crest of teeth directly, it occurs deformation strongly, fibrous tissue will occur severe deformation, fiber streamlines density becomes the most intensive, and the work hardening phenomenon in (Z2) is obvious. The zone (Z3) indicates the flank of internal thread which is acted by the adjacent ridges simultaneously, the metal material will flow along the flank of tap teeth from (Z2) to (Z3), the acted pressure and fiber streamlines density become smaller compared with that of zone (Z2).

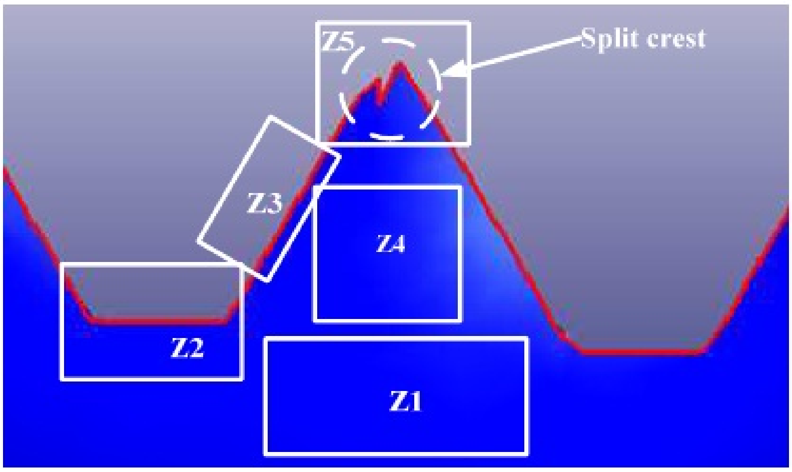


Fig. 20. Metallurgical characteristic of forming thread [23].

The zone (Z4), the inside of internal thread, under slight extrusion, and the deformation degree drops with the distance from surface increases. The zone (Z5), the crest of internal thread, also the free region, under the smallest pressure, the metal material of this region mainly flows from the thread flank and the flow rate is higher than that of the zone (Z4), then forms split crest in thread and the fiber streamlines density becomes sparse, split crest is a serious fault of extrusion tapping of internal thread [23].

The analysis of metal plastic flow law was conducted based on the simplified scratch simulation, as it shown in Fig. 21. During the experiment of thread extrusion forming process, the material will not only flow along radial direction and fill the required height of thread, but also flow along the extrusion direction. In the side view, the metal plastic flow velocity in the region before the crest of teeth is higher than other region, and a special metal plastic wave is formed. In the front view, the metal plastic flow velocity in the region contacted with crest of teeth is the highest, and then the metal will flow along the flank of teeth. Due to the extrusion degree to metal of crest is more serious than that of the flank, this difference results in a higher metal plastic velocity along crest of teeth than that along flank of teeth. The metal plastic flow law obtained from this simulation was consistent with the theoretical analyzed results [23].

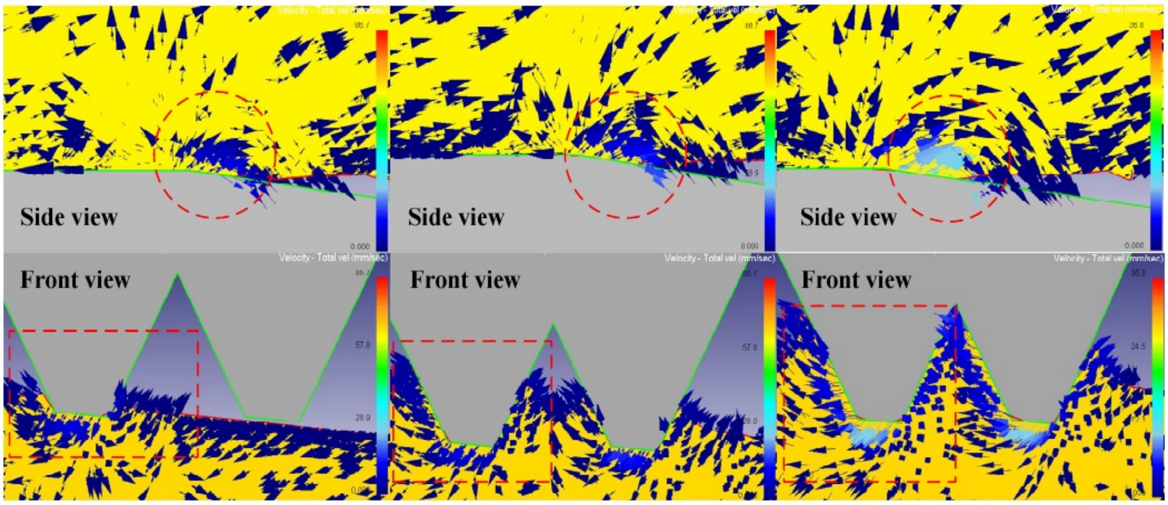


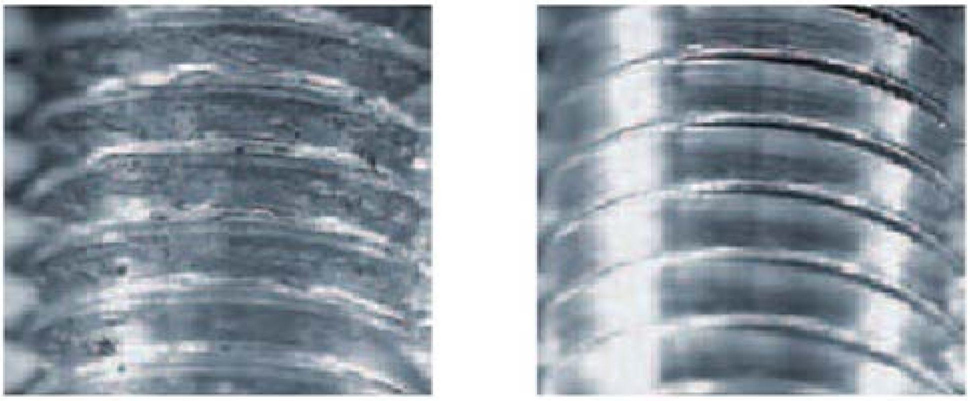
Fig. 21. Metal flow velocity [23],

a) cross-section of scratch 3, b) cross-section of scratch 10, c) cross-section of scratch 15.

As tap is moving and forming the thread in the direction of torsion, plastic deformation in the metal occurs under the action of the forming forces at the point of contact of the tap’s lobes with the material. The maximum value of plastic deformation will be reached at the moment when the thread is completely formed, scratch 15, Fig. 21. The analysis of specific forces during cutting and forming tap threading will be thoroughly described in the next chapter.

3.2 Lubrication in form tapping

Warmth occurs as a result of applying work when metal is machined. Acting on a cutting tool, the heat softens it, makes it less wear resistant and changes its dimensions; under the action of the heat the sizes of the workpiece changing, which reduces the machining accuracy. In the process of metal machining approximately 85–90 % of all the work is converted into heat energy, the amount of which (in the contact area) significantly affects to the wear and tool life, roughness of machined surface. It was established that over 70 % of this heat is carried away by chips (in form tapping this part of heat is absorbed by the workpiece and the tool), 15-20 % is absorbed by the tool, 5-10 % is absorbed by the workpiece and only 1 % is radiated in the surrounding space. The temperature in the contact zone between tool and the workpiece depends on the physical and mechanical properties of workpiece material, machining parameters, the geometric parameters of the cutting tool and applying of lubricant or coolant [32].
The major role of lubricating oil is to decrease the friction between the tool and the workpiece and consequently reduce the cutting forces and the tool wear. In addition, the cutting fluids have to remove the heat due to metal deforming and perform the chemical reactions under boundary conditions with the workpiece surface to prevent the welding of the tool [6].
In the case of form tapping of steels with lubrication, the fluid contributes to lubrication predominantly by a physicochemical process due to the additives it contains. Form tapping is a severe process of machining and the success of this operation often depends on the lubricant, Fig. 22. Moreover, if compare with cut tapping, form tapping is quite sensitive to lubricant applying.
When the tool is made from heat resistant materials, heat plays a positive role, as in the machining zone the workpiece material is softening and its reduce machining forces.



a b

Fig. 22. Influence of lubrication in form tapping [17], a) flaked surface from insufficient lubrication b) smooth surface with sufficient lubrication.

However, in most cases the resistance of the cutting tool and productivity are decreased as a result of increasing temperature in the contact zone. To improve heat dispersion from the contact zone and reduce the coefficient of friction cooling lubricants are applied.

The choice of coolant depends on the material of the workpiece and type of machining. The coolant must have high cooling and lubricating properties, corrosion protection and be environmentally friendly for operating personnel. According to the chemical composition and physical properties coolants are divided into two main groups [32]:

1) Water-based solutions, that contain small amount of alkali metal salts. Oils with additives of sulphur and chlorine compounds. The cooling capacity of these types of coolants is lower than cooling capacity of water. Thus, the cooling capacity of water-based solutions is 80-90 % (depending on concentration), the oil emulsion — 30-80 %, oil — 25 % of the cooling capacity of water. Water-based solutions have high cooling capacity and detergent properties. Disadvantages of this group are unfavourable affects to the surfaces of the machine and lubrication of the bearings.

2) Oil emulsions, where the oil is distributed in the form of small droplets, obtaining spherical forms under the action of surface tension. For the stability of such emulsions in their composition the emulsifier introduces. The emulsifier creates the adsorption films on the surfaces of droplets, which prevents droplets from oil adhesion together with the additives of sulphur. Sulfur additive allows to reduce the power consuming of the cutting process and increase the tool life.

In that way, applying of coolants in metals machining allows to increase the productivity of equipment, improve accuracy of machined surfaces and reduce their roughness, reduce defective production.

In article [31] was described influence of applied lubricants on form tapping process. There were 9 oils and 2 water-based emulsions from different manufactures, their names were hidden. All of these fluids mainly based on either sulphur or chlorine, Table 2.

Table 2. Values of the kinetic viscosities and designations of the chemical elements [31].

	Kinetic viscosity at 40 °C (mm^2/s)	**Chemical elements of additives**	**Manufacturer**
Oil no. 1	15	S+Ca	M1
Oil no. 2	20	S+Na	M2
Oil no. 3	11	S+Ca+P+Zn	M2
Oil no. 4	21	Cl	M3
Oil no. 5	12	Cl	M2
Oil no. 6	9.9	S+Ca+P+Zn	M4
Oil no. 7	11.7	Cl+S+P+Na	M4
Oil no. 8	22	S	M4
Oil no. 9	17	S+P+Ca	M5
5% Emul. no. 1	2	S+P+Na+K	M6
20% Emul. no. 2	2	S+Na+P+K	M2

The work material, machine center and machining parameters were similar for each lubricant. Also, all drilled holes were calibrated before threading for achieving an accurate hole axis straightness. New forming taps, coming from the same batch and cleaned with acetone, were used for each lubricants, and each was tested several times [31].

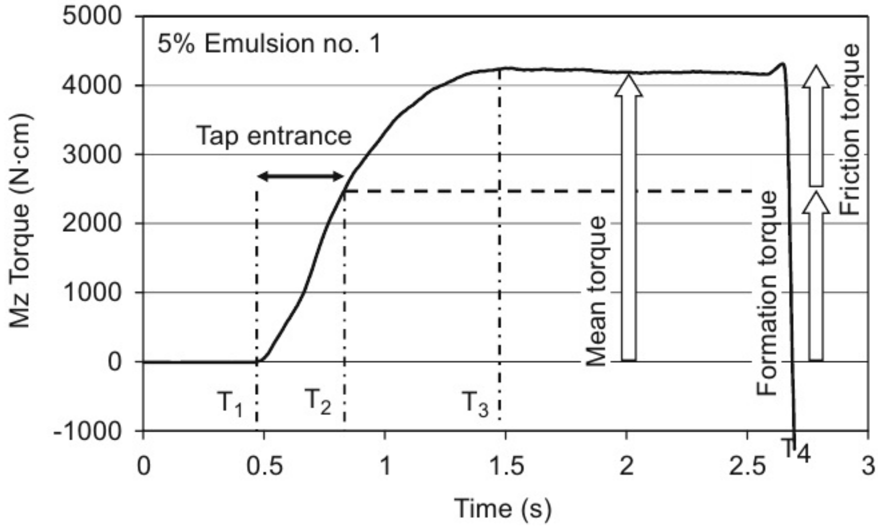


Fig. 23. Evolution of the torque during thread forming [31].

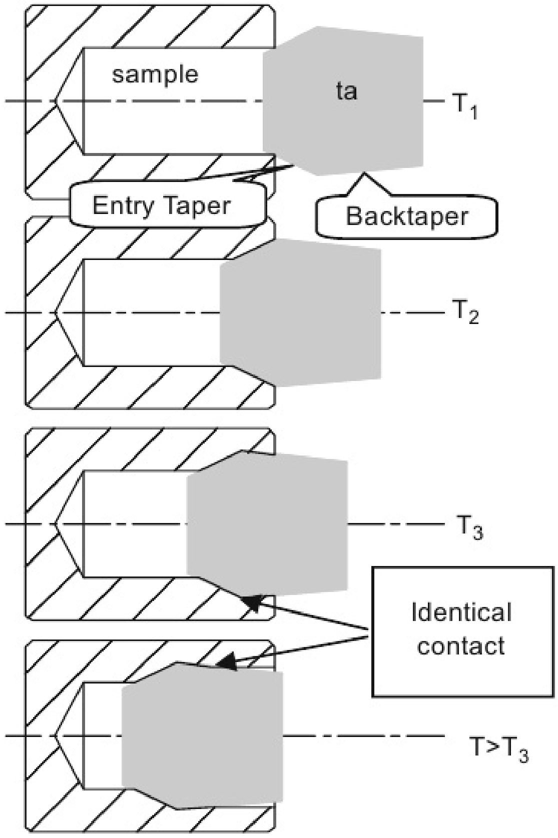


Fig. 24. Positions of the tap during threading [31].

There are four time intervals at this experiment, Fig. 23 and Fig. 24. As forming taper penetrates the workpiece the torque increases from time T_1 to T_2. At time T_2 all the taper lobes are forming the material and the first thread is completely formed. According to the article [31], the value of the torque at this moment is called the formation torque. After time T_2 the torque proceeds increasing due to the increasing of contact surface between the workpiece and the tap resulting from springback of the deformed material. At time T_3 the area of the surface contact will not increase and consequently, if the lubricant is still remaining active, the torque will remain constant. The increase of the torque from T_2 to T_3 is named friction torque. At time T_4 the tap stops and travel out of the workpiece, the torque is becoming negative. The mean torque was calculated during the steady state from time T_3 to T_4 [31].

Results of the experiment are shown in Fig. 25. Lubricants were rated from best to worst by considering the mean torque.

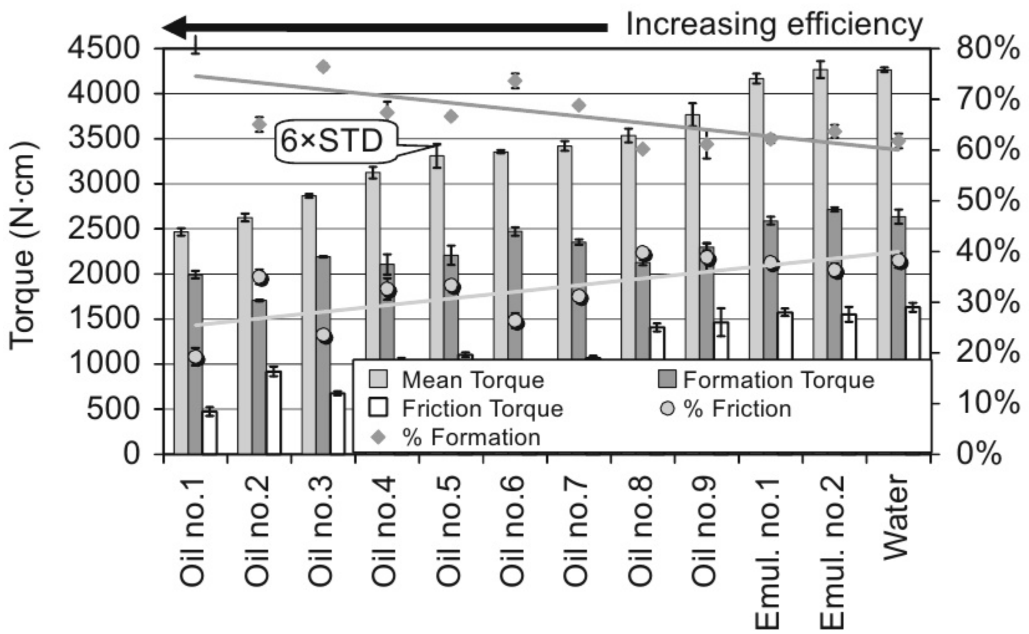


Fig. 25. Torque results for each lubricant [31].

The efficiency of lubricant depends mostly on its additives. As it mentioned in article [31], the first four lubricants show decreasing efficiency, where oils no.5 to no.7 have a comparable mean torque and the last four also present a decreasing efficiency. Oils with chlorine additives do not rank well. Chlorinated additives are used less and less due to the health of workers and environmental issues.

If compare the most efficient lubricant, oil no.1, with the worst efficient, emulsion no.2, the mean torque is 40% less in case of oil no.1, and statistically average formation efficiency is more than 13% in case of oil no.1. It is very important to reduce torque in form tapping together with increasing the formation efficiency, because it reduces forming forces, positively affects on tap durability, therefore it reduces the production costs.

3.3 Comparison of forming and cutting taps

Summarizing the information from written above, it is possible to compare forming taps and cutting taps. Results of comparison are noted in Table 3. According to the articles [10, 17, 23, 28, 31], it can be written, that forming taps are better then cutting taps in next parameters:

1. Chipless tapping. Since the thread is formed and not cut, there are no chips to interfere with the tapping process or to cause chip-removal problems in blind holes, as it shown in Fig. 26.

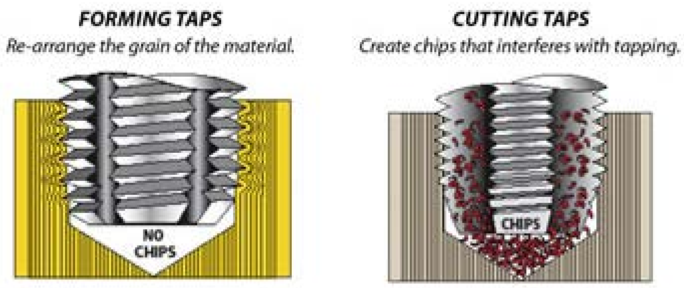


Fig. 26. Comparison of forming and cutting taps [10].

2. Stronger threads. The grain flow of formed threads follows the contour of the thread resulting in greater thread strength. This is especially true for materials that work-harden such as steel and stainless steel.
3. Stronger taps. The absence of chips eliminates the need for flutes, resulting is a solid, stronger tap.
4. Longer tap life. Forming taps last 3 to 20 times longer than cutting taps because they have no cutting edge to dull.
5. More efficient production. Less tap breakage, and faster tapping speeds combine to reduce cycle time and machine downtime.
6. Ideal for non-lead screw tappers. The ability to form their own leads makes taps especially well suited for CNC machines or other machines without lead screws.

But on the other point of view, there are also disadvantages of forming taps:

1. Production costs resulting from accurate core holes.
2. Necessity to apply significant torque (2-3 times more comparatively to cutting tap).
3. Only materials with high plasticity can be machined.
4. Increased tool requirements (toughness and durability).
5. Impossible to apply in industries where tightness required because of geometry of the thread.

Table 3. Comparison of cutting and forming taps.

	Advantages	**Disadvantages**
Cutting	• No special requirements for the machine • Almost all machinable materials can be processed	• Chip removal • Reduced tool stability due to flutes, increased risk of fracture
Forming	• Chipless threading • Higher precision • Low risk of fracture because of stable tool • Better surface quality. • High static and dynamic strength of the thread • Longer tool life • Through holes and blind holes with one tool	• Tighter tolerance of the core hole increases the production costs • Not acceptable for food industry, the medical and aerospace industry • Increased tool requirements • Significant torque • Increased lubricant requirements

4 ANALYSIS OF SPECIFIC FORMING FORCES AT MANUFACTURE OF THE THREADS, COMPARED WITH SIMILAR RESULTS FOR CUTTING TAPS

4.1 Threading by cutting taps

In this cutting process, which is demonstrated at Fig. 27, cutting forces act at contact points between cutting edge of every thread of cutting tap and workpiece. It is important to know how material removal mechanic acts in this tapping process to analyze possible defects and increase the efficiency. In this paragraph special cutting forces will be defined in order to describe the material removal mechanic in threading by cutting taps.

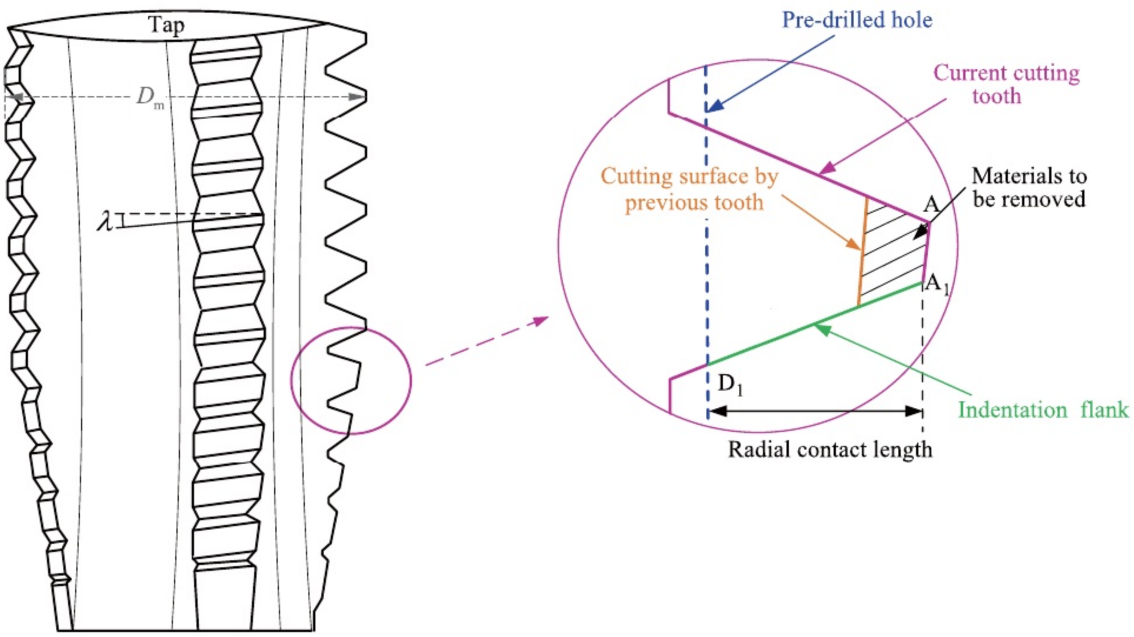


Fig. 27. Tapping process geometry [11].

In ideal tapping process, the spindle should feed one pitch P once the tap has a full revolution. However, in actual case, there may exist feed error δ, which is defined as the deviation between the actual axial feed per revolution and the pitch of the thread. This phenomenon, which is shown on Fig. 28, will lead to that the tap feeds less or more than one pitch P. Note that the basic profile of the thread is shown in Fig. 6.

According to the article [11], feed error could be calculated as:

$$\delta = v_f \times T - P \tag{1}$$

where v_f [mm.min^{-1}] – feed velocity,

T [min] – spindle period,

P [mm] – pitch.

If the result of δ obtained from Eq. (1) is positive, the tapping process is in overfeed case, otherwise, it is in underfeed case.

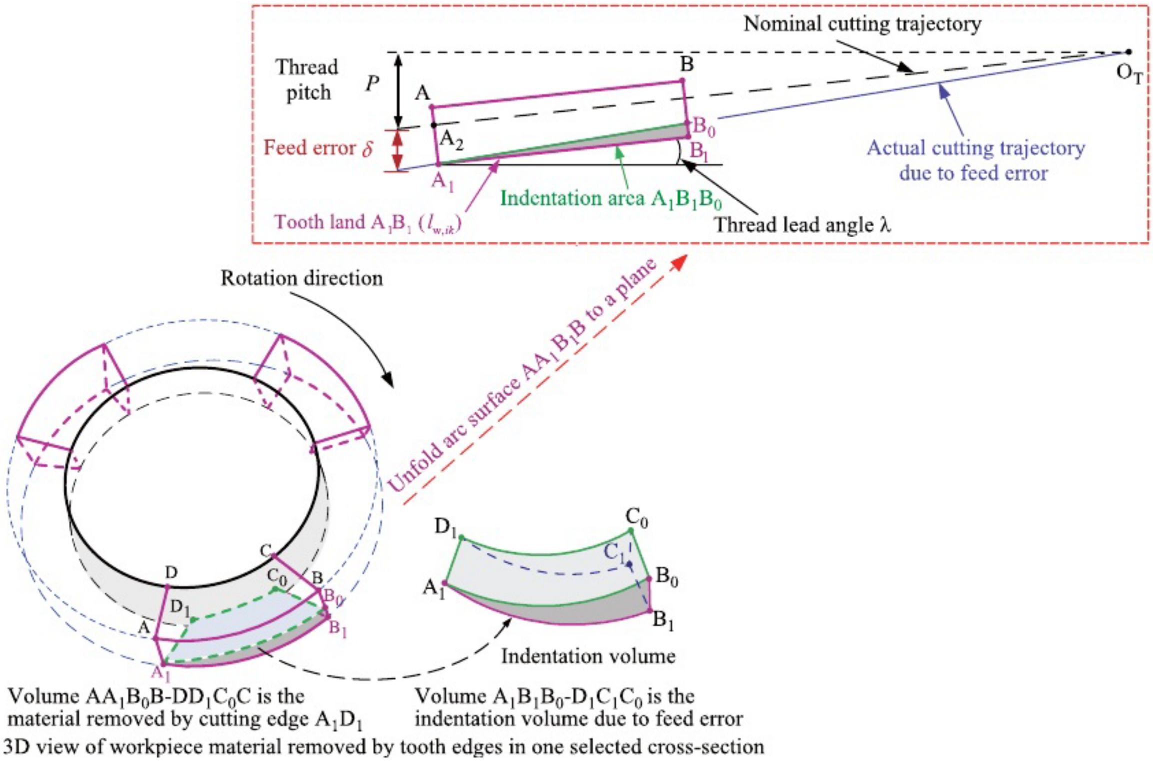


Fig. 28. Feed error illustration [11].

Due to the occurrence of feed error δ, the flank land of the tap will indent into the machined surface left by previous cut, hence, some of the material will be pressed down under the flank of the cutting edge, resulting in the appearance of indentation force $F_I(t)$. In tapping process, besides the indentation force $F_I(t)$ induced by feed error δ, regular cutting force $F_C(t)$ due to material removal mechanism is another important source of tapping force. The resultant tapping force $F(t)$ can be mathematically expressed as [11]:

$$F(t) = F_C(t) + F_I(t) \tag{2}$$

As the cutter penetrates into the workpiece, the teeth of the back tapper of the tool will indent the threaded wall due to the existence of feed error. As a result, indentation effect of the back tapper will also contribute to the total cutting forces. Based geometric relationship in Fig. 29, the total indentation forces $F_I(t)$ in global X–Y–Z coordinate system can be obtained by:

$$F_I(t) = \begin{bmatrix} F_{X,I}(t) \\ F_{Y,I}(t) \\ F_{Z,I}(t) \end{bmatrix} = T_3(t) F_{p,I} \tag{3}$$

with [11]:

$$T_3(t) = \begin{bmatrix} -\cos\alpha \sin\theta_{ij}\ (t) \\ -\cos\alpha \cos\theta_{ij}\ (t) \\ \sin\alpha \end{bmatrix} \tag{4}$$

where $F_{p,I}$ – intendation force.

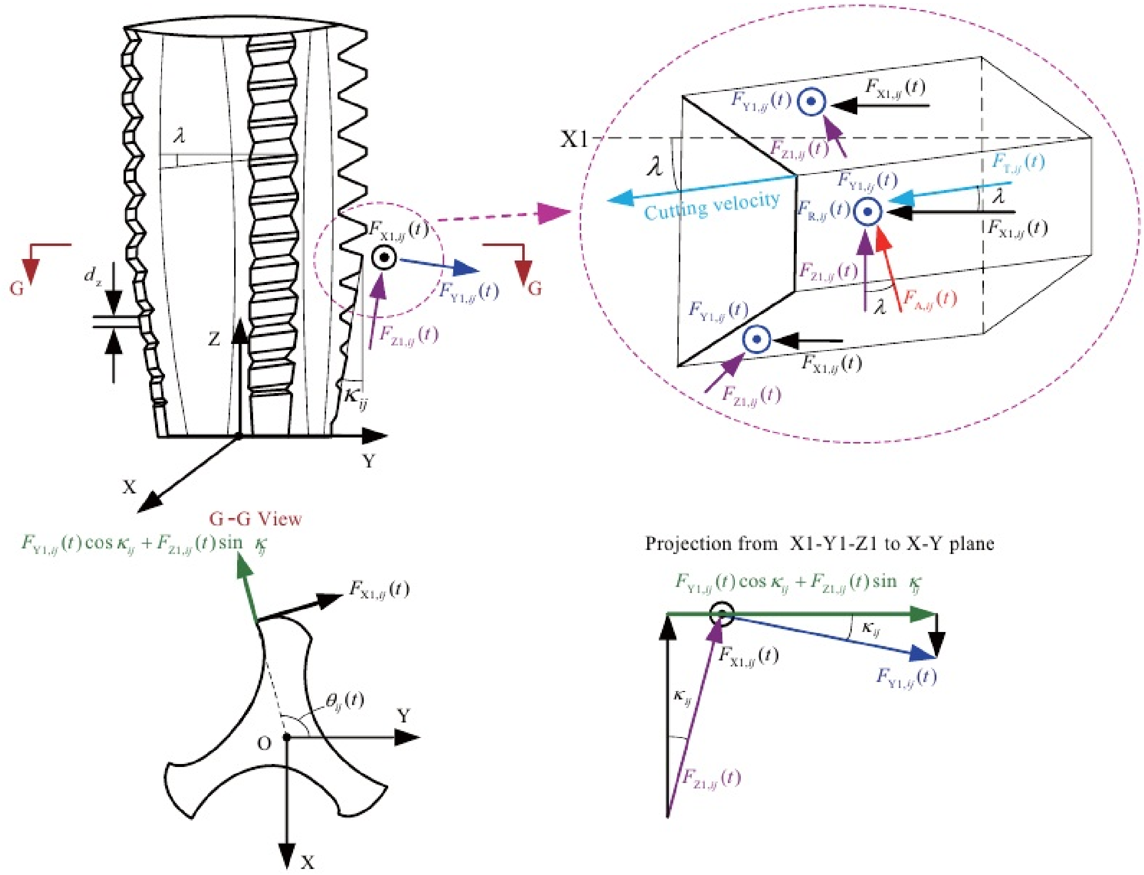


Fig. 29. Schematic diagram of cutting process for a tapping process [11].

It should be mentioned, that during the research, described in [11], the tap was discretized into a finite number of axial disk elements with equivalent axial length d_z. The tangential ($F_{T,ij}(t)$), radial ($F_{R,ij}(t)$) and axial ($F_{A,ij}(t)$) cutting forces related to the *j*th disk element of the *i*th tap edge can be expressed as:

$$F_{T,ij}(t) = \frac{K_T h_{ij}(t) d_z}{\cos\, k_{ij} F_{R,ij}(t)} \tag{5}$$

$$F_{R,ij}(t) = \frac{K_R h_{ij}(t) d_z}{\cos\, k_{ij} F_{A,ij}(t)} \tag{6}$$

$$F_{A,ij}(t) = \frac{K_A h_{ij}(t) d_z}{\cos\, k_{ij}} \tag{7}$$

where the instantaneous uncut chip thickness related to the *j*th disk element of the *i*th tap edge, i.e. $h_{ij}(t)$, can be calculated by:

$$h_{ij}(t) = a_{e,ij}(t) \cos k_{ij} \tag{8}$$

with

$$k_{ij} = \begin{cases} k_c, & \text{if major cutting edge UL is on the chamfer part} \\ 0, & \text{if major cutting edge UL is on the cylindrical part} \\ \frac{\pi}{2} - \frac{\alpha}{2}, & \text{for minor cutting edge WU} \\ \frac{\pi}{2} + \frac{\alpha}{2}, & \text{for minor cutting edge LK} \end{cases} \tag{9}$$

where K_T, K_R, K_A – shearing force coefficients,

$a_{e,ij}(t)$ – defined as the radial distance between current cut and the previous one, as shown in Fig. 30.

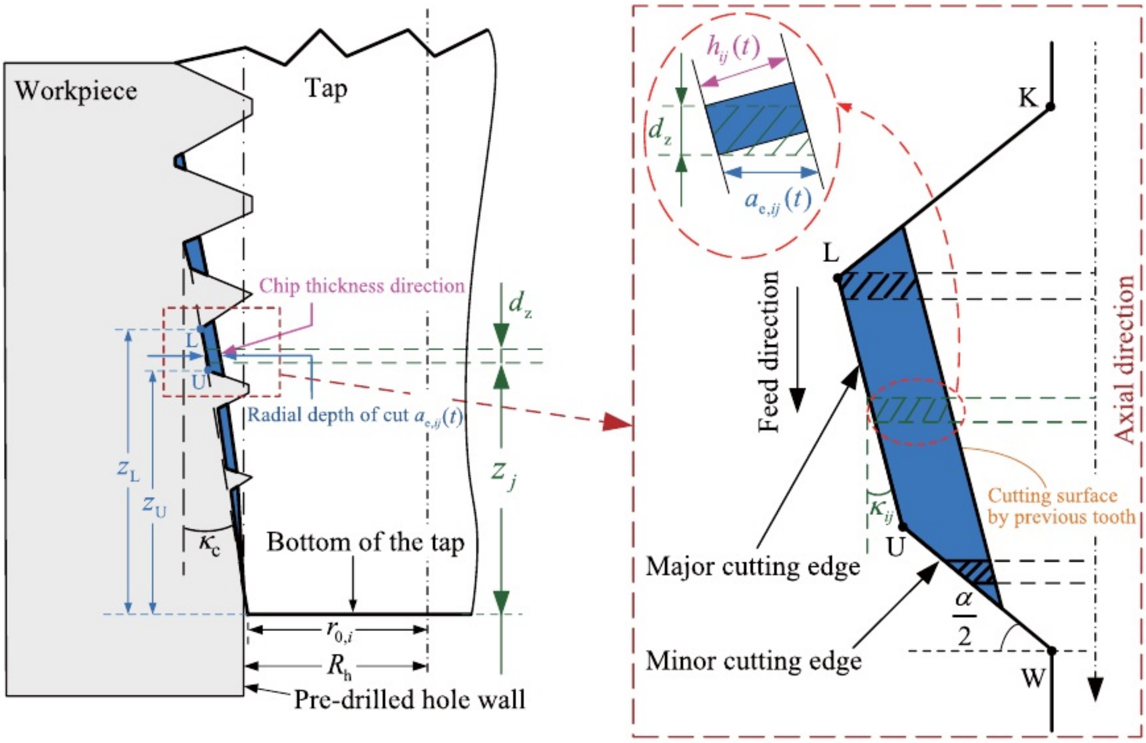


Fig. 30. Chip geometry of tapping process [11].

From this definition it can be seen that $a_{e,ij}(t)$ relates to the rotational radii of the cutting edges in the previous and the current cuts. Actually, since the tap's tooth ‘copies’ its own shape on the workpiece as cutting continues, the rotational radius $r_{ij}(t)$ of the jth disk element of the ith tap edge at t equals the geometrical radius R_{ij} of the concerned disk element, and it can be expressed as the function of the axial and radial positions according to the actual geometry of the disk element [11]:

$$r_{ij}(t) = R_{ij} = \begin{cases} r_{o,i} + z_j \tan k_{ij}\,, & \text{for major cutting edge UL} \\ r_{o,i} + z_U \tan k_{ij} - \frac{z_U - z_j}{\tan\frac{\alpha}{2}}, & \text{for minor cutting edge WU} \\ r_{o,i} + z_L \tan k_{ij} + \frac{z_L - z_j}{\tan\frac{\alpha}{2}}, & \text{for minor cutting edge LK} \end{cases} \tag{10}$$

where z_U and z_L are the axial distances between points *U*, *L* and the bottom of the tap [11], as shown in Fig. 30. By using equivalence (10), $a_{e,ij}(t)$ can be obtained as:

$$a_{e,ij}(t) = \begin{cases} r_{ij}(t) - r_{(i-1)(j-1)}\left(t - \frac{T}{N_t}\right), 2 \le i \le N_t \\ r_{ij}(t) - r_{(N_t)(j-1)}\left(t - \frac{T}{N_t}\right), i = 1 \end{cases} \tag{11}$$

where *n* means that the current disk element is to remove the surface generated by the *n*th previous disk element, and can be expressed as:

$$n = \text{int}\left(\frac{P}{N_t d_z}\right) \tag{12}$$

It should be noted that the cutting forces obtained from Eqs. (5), (6) and (7) are in the local coordinate system, as shown in Fig. 29. Based on the geometric relationship shown in Fig. 29 and Fig. 30, the cutting forces can be transformed from the local coordinate system to global *X-Y-Z* coordinate system as follows:

$$\begin{bmatrix} F_{X,ij}(t) \\ F_{Y,ij}(t) \\ F_{Z,ij}(t) \end{bmatrix} = T_2 \begin{bmatrix} F_{X1,ij}(t) \\ F_{Y1,ij}(t) \\ F_{Z1,ij}(t) \end{bmatrix} \tag{13}$$

with

$$\begin{bmatrix} F_{X1,ij}(t) \\ F_{Y1,ij}(t) \\ F_{Z1,ij}(t) \end{bmatrix} = T_1 \begin{bmatrix} F_{T,ij}(t) \\ F_{R,ij}(t) \\ F_{A,ij}(t) \end{bmatrix} \tag{14}$$

where T_1 and T_2 are transformation matrices from transforming the local *T-R-A* coordinate system to *X1-Y1-Z1* and from *X1-Y1-Z1* to global *X-Y-Z* system:

$$T_1 = \begin{bmatrix} \cos\lambda & -\sin\lambda & 0 \\ \sin\lambda & \cos\lambda & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{15}$$

$$T_2 = \begin{bmatrix} \cos\lambda & -\sin\lambda & 0 \\ \sin\lambda & \cos\lambda & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{16}$$

where λ can be obtained by [11]:

$$\lambda = \arctan\frac{P}{\pi D_{nom}} \tag{17}$$

Total cutting forces applied on the tap can be obtained by summingelemental cutting forces of all disk elements:

$$F_C(t) = \begin{bmatrix} F_{X,C}(t) \\ F_{Y,C}(t) \\ F_{Z,C}(t) \end{bmatrix} = \begin{bmatrix} \sum_{ij} F_{T,ij}(t) \\ \sum_{ij} F_{R,ij}(t) \\ \sum_{ij} F_{A,ij}(t) \end{bmatrix} \tag{18}$$

Finally, calculation of the reluctant tapping force F(t) can be achieved by substituting of Eqs. (3) and (18) into Eq. (2) [11].

The resulting thrust force and resulting torque can be calculated as the sum of all forces of immersed cutting edges [26]:

$$F_{thr} = \sum_{i=1}^{n} F_a(i) \tag{19}$$

$$M = \frac{d}{2} \sum_{i=1}^{n} F_t(i) \tag{20}$$

4.2 Threading by forming taps

As it was mentioned in third chapter, not all materials are suitable for thread forming. For that, they must have a minimum value of ductility and must not exceed a certain maximum strength. Suitable materials usually have a tensile strength of less than 1400 N/mm^2 and a minimum fracture strain of 5 % [24].

In a form tapping operation, each tooth on the entry taper of the tap acts as a forming tool. As each tooth on the entry taper comes into contact with the workpiece, it deforms the workpiece material in front of it. This deformed material flows upwards along the faces of the tooth and is deposited on the sides of the grooves formed by the tooth. This deposition is known as a ridge. These ridges increase in height as more and more material from the grooves flows out with each successive tooth deforming the workpiece to greater depths, and ultimately assume the shape of the crests of the final thread form.

The forces developed during the process are both due to the deformation of the workpiece material and the resulting flow of the deformed material along the faces of the tooth. Since there is always an elastic portion beneath the plastically deformed material that tries to recover once the forces causing the material to deform are removed, there will be an increase in the forces experienced during the process. Plastic deformation will also result in the work hardening of the workpiece material. Thus, the two major factors contributing to the forces during a forming process are the deformation of the material by the tool and the elastic recovery of the material [25].

As it mentioned in article [25], to simplify the analysis of the internal thread forming process, the initial focus was on the mechanisms at the tooth level, i.e. the determination of the nature of forces experienced by a single tooth as it deforms the workpiece material. Special forming tool was developed, where all but two axially-consecutive teeth on a form tap were removed to capture the forces developed due to the flow of deformed material in between these teeth. To maintain orthogonal contact, the tool was moved on the workpiece at an angle equal to the lead angle (γ = 2.73 degrees) of the tap as shown in Fig. 31.

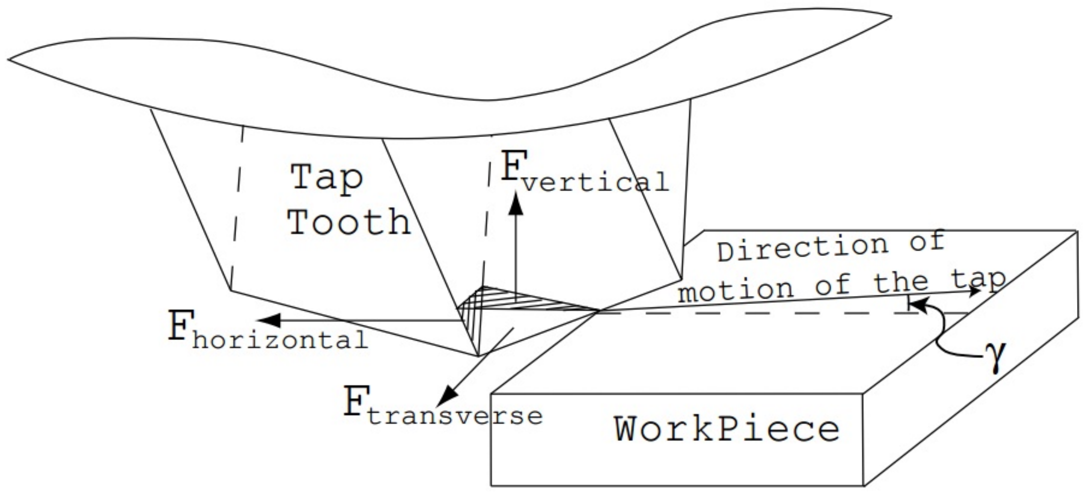


Fig. 31. Single tap tooth [25].

The isometric view of Fig. 32 shows the material flow angle, η_l, which is the angle between the frictional force, F_{fl}, and the perpendicular to the edge 4-3. There will be a similar angle, η_t, on the trailing face of the tooth between the frictional force, F_{ft}, and the perpendicular to the edge 4-2. In the side view, the depth of engagement of the tooth, *h*, in the workpiece can be seen. The top view shows the y-component of distance between point 1 and point 4, *p*, and the y-component and z-component of distance between point 4 and point 3 or point 2, *q* and *v*, respectively. α is called the thread angle of the given thread form, and β is the relief angle of the tooth. The normal force, F_n, and frictional force, F_f , on each face are assumed proportional to the area of contact between that face and the workpiece. Thus, the forces on the *i*th tooth are given as:

$$\begin{aligned} F_{nt}(i) &= C_n(i)A_t(i) \\ F_{nl}(i) &= C_n(i)A_l(i) \\ F_{ft}(i) &= C_f(i)A_t(i) \\ F_{fl}(i) &= C_f(i)A_l(i) \end{aligned} \tag{21}$$

where $A(i)$ represent the areas of the faces of the tooth in contact with the workpiece when viewed along the direction of motion of the tooth and the subscripts t and l represent the trailing and leading faces, respectively. The $C(i)$ represent the proportionality constants henceforth called the specific forming energies.

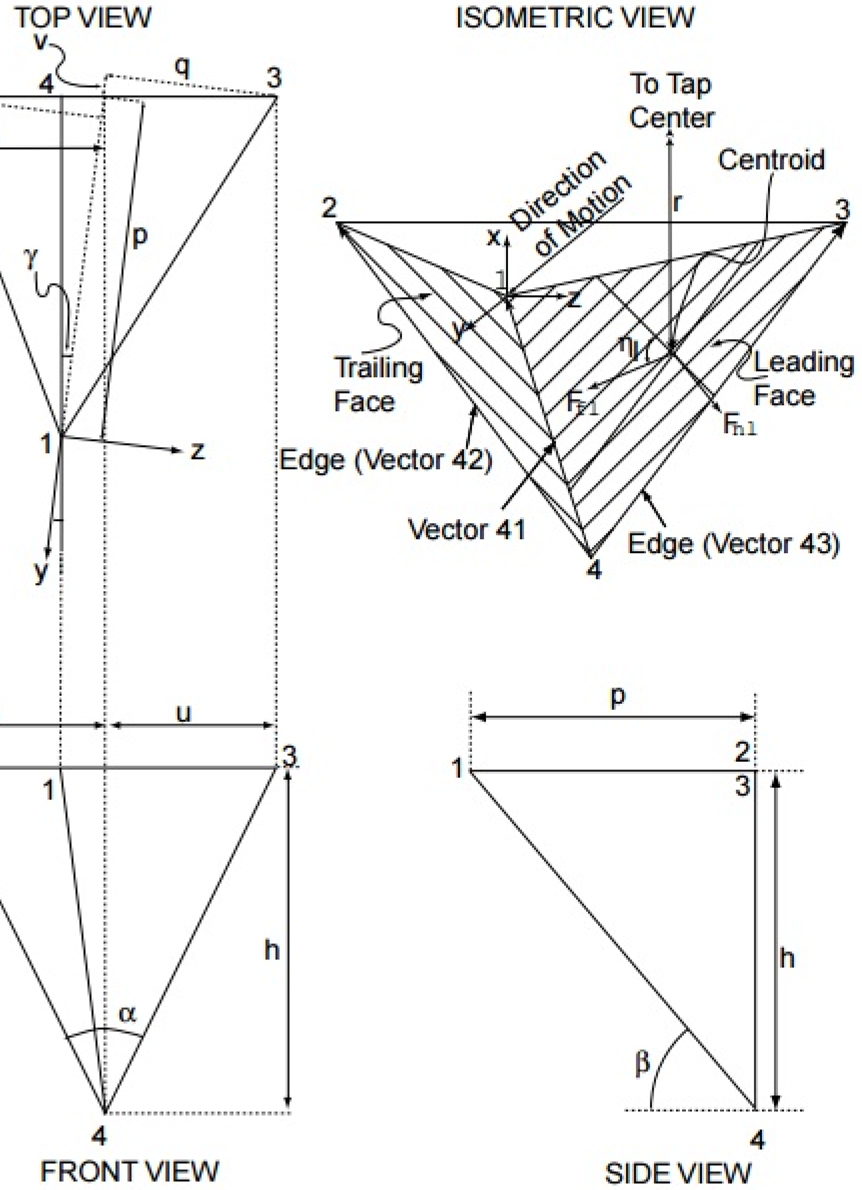


Fig. 32. Geometry of a single tap tooth [25].

As it mentioned in article [25], that the forces during internal thread forming are dependent on the surface speed of the tool on the workpiece and the depth of cut. To depend these parameters with specific forming forces, following equalities were obtained [25]:

$$\begin{aligned} \ln C_n\,(i) &= a1 + a2 \ln h(i) \ln S\,(i) + a3 \ln h(i) + a4 \ln S(i) \\ \ln C_f\,(i) &= b1 + b2 \ln h(i) \ln S\,(i) + b3 \ln h(i) + b4 \ln S(i) \end{aligned} \tag{22}$$

where a and b are determined from calibration experiments for a given tool-workpiece combination and $S(i)$ is the surface speed of the *i*th tooth and is given as:

$$S(i) = (2 \times N_s \times (h(i) + H))/60 \tag{23}$$

where N_s is the spindle speed in rpm. $h(i)$ is the depth of engagement of the *i*th tooth with the workpiece. *H* is a hole radius. If the total number of the teeth on the entry taper are *K*, then $h(i)$ is given by:

$$h(i) = d(i) - H, \qquad \text{if } d(i) > H$$
$$h(i) = 0, \text{ if } d(i) \le H \tag{24}$$
$$d(i) = d_{min} + (i-1)\Delta d$$
$$\Delta d = (d_{max} - d_{min})/K$$

The area shaded by single hatching in Fig. 33 shows the areas of contact between the

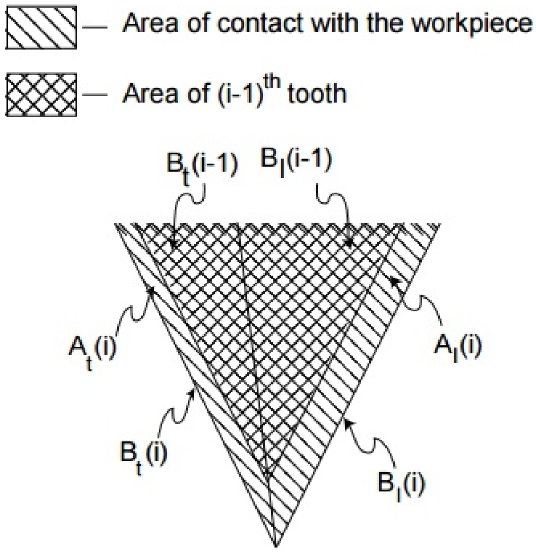


Fig. 33. Areas of contact of *i*th tooth [25].

trailing and leading tooth faces and the workpiece. These areas are given by:

$$A_l(i) = B_l(i) - B_l(i-1)$$
$$A_t(i) = B_t(i) - B_t(i-1) \tag{25}$$

where the $B(i)$ give the total area of the tooth shown by the cross-hatched region in Fig.33. These areas are given as:

$$B_l(i) = \left|\overrightarrow{43} \times \overrightarrow{41}\right| = -p(i)q(i)\hat{x} + h(i)q(i)\hat{y} + h(i)(p(i) + v(i))\hat{z}$$
$$B_l(i) = \left|\overrightarrow{41} \times \overrightarrow{42}\right| = -p(i)q(i)\hat{x} + h(i)q(i)\hat{y} - h(i)(p(i) - v(i))\hat{z} \tag{26}$$

where $\hat{x}$, $\hat{y}$ and $\hat{z}$ are the unit vectors in the *x*, *y*, and *z* directions, respectively. $p(i)$, $q(i)$, and $v(i)$ may be evaluated from Fig. 32 as follows [25]:

$$p(i) = h(i)/\tan\beta$$
$$q(i) = u\cos\gamma$$
$$v(i) = u\sin\gamma \tag{27}$$
$$u(i) = h(i)/\tan(\alpha/2)$$

The normal and frictional forces can subsequently be transformed into the *x*, *y*, and *z* axes defined in Fig. 32 by using transformation equations as given by [25]:

$$\begin{aligned} F_x &= (\vec{F}_{fl} + \vec{F}_{nl} + \vec{F}_{ft} + \vec{F}_{nt}) \cdot \hat{x} \\ F_y &= \left(\vec{F}_{fl} + \vec{F}_{nl} + \vec{F}_{ft} + \vec{F}_{nt}\right) \cdot \hat{y} \\ F_z &= \left(\vec{F}_{fl} + \vec{F}_{nl} + \vec{F}_{ft} + \vec{F}_{nt}\right) \cdot \hat{z} \end{aligned} \tag{28}$$

Refering to Fig. 34, obtained forces are then transformed into tap coordinates using the

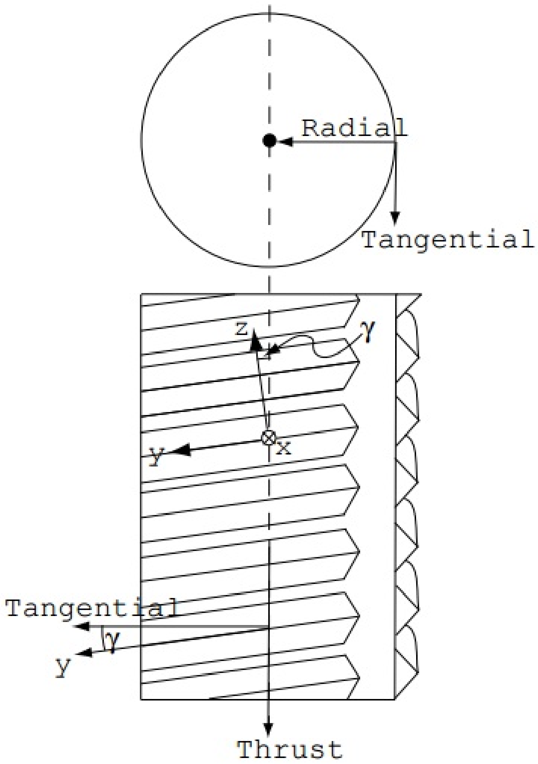


Fig. 34. Transformation from local coordinates to global [25].

following equations:

$$\begin{aligned} F_{thr} &= F_y \sin\gamma + F_z \cos\gamma \\ F_{tan} &= F_y \cos\gamma - F_z \sin\gamma \end{aligned} \tag{29}$$

where F_{thr} and F_{tan} are the forces in the thrust and tangential directions, respectively. The torque, M, on the tooth during forming can be determined by taking the product of the force in the tangential direction, F_{tan}, with r, the radial distance of centroid of the tooth from the center of tap:

$$M = F_{tan} \cdot r \tag{30}$$

Torque, in the cold forming of threads, depends mostly on the workpiece material, the thread size, lubrication and preparatory diameter, as well as on the geometry and the coating of the tool [20, 24].

5 DESIGN EXPERIMENT AND IT IMPLEMENTATION

The main goal of experiment was to compare torques while threads were formed by forming tap, Fig. 35. For the experiment one forming tap was used for threading three holes. Parameters of the tap, that was made by company Emuge, are shown in Table 4. Cutting parameters were similar for every experimentally formed thread.

Fig. 35. Forming tap, that was used for experiment.

Table 4. Technical parameters of the tap.

Parameters	Value
Marking by firm	821356-498
Nominal Diameter	M10
Pitch	1,5
Length of tap	100
Material	HSS
Coating	TiN
Quantity of lobes	5
Quantity of flutes	5

Experiment's technique

For all three internal threads one kind of material was used. It was steel 15142, according to ČSN, or 42CrMo4 in DIN standard. Chemical composition is described in Table 5 and mechanical characteristics are described in Table 6. The steel 42CrMo4 is often used for mechanical components that require hardening, particularly for mechanical application that require high wear and fatigue contact resistances.

Table 5. The mechanical composition of steel 42CrMo4 [29].

Material	Composition, [%]						
42CrMo4	C	Mn	P	S	Si	Cr	Mo
	0,38-0,45	0,60-0,90	Max. 0,025	Max. 0,035	Max. 0,40	0,90-1,20	0,15-0,30

Table 6. Mechanical properties of steel 42CrMo4 [29].

Parameters	Value
R_m, Tensile strength	620 MPa
$R_{p0,2}$, 0,2% proof strength	480 MPa
A, min. elongation at fracture	4 %
Z, reduction in cross section on fracture	45 %
Vickers hardness	195 HV

Sizes of workpiece were 100x42x30.

Machine TAJMAC-ZPS MCV 1210 with control system SINUMERIK 840 was applied for this experiment. This machine, shown in Fig. 36, can treat the workpiece in three or five axes. Positions in X, Y and Z axes are measured out with high accuracy by absolute measured units. All main parameters of the machine described in Table 7.

Fig. 36. Machine TAJMAC-ZPS MCV 1210 [20].

Table 7. Machine parameters [20].

Swing	
X axe	1 000 mm
Y axe	800 mm
Z axe	600 mm
Work table	1 200 x 1 000 m
Maximal weight of workpiece	3 000 kg
Engine	
Type	electric
Maximal speed	18 000 min^{-1}
Maximal power	32 kW
Maximal torque	90 Nm

Machining parameters

For this experiment forming parameters, that describes in Table 8, were used. Also, as lubricant was used water miscible metalworking fluid CIMSTAR 597 of company CIMCOOL.

Table 8. Parameters of forming, applied in the experiment.

Parameters	**Value**
Depth of thread	20 mm
Depth of forming	0,33 mm
Forming speed	10 m/min
Spindle speed	320 rev/min
Feed per revolution	1,5 mm/rev
Coolant	emulsion 9%

It is necessary to write, that all the holes in the workpiece were preparatory drilled and chamfered before threading.

Measurement of torque

For the experiment piezoelectric quartz dynamometer KISTLER 9272 was used for obtaining accurate results. This dynamometer can be connected with a computer (Fig. 37).

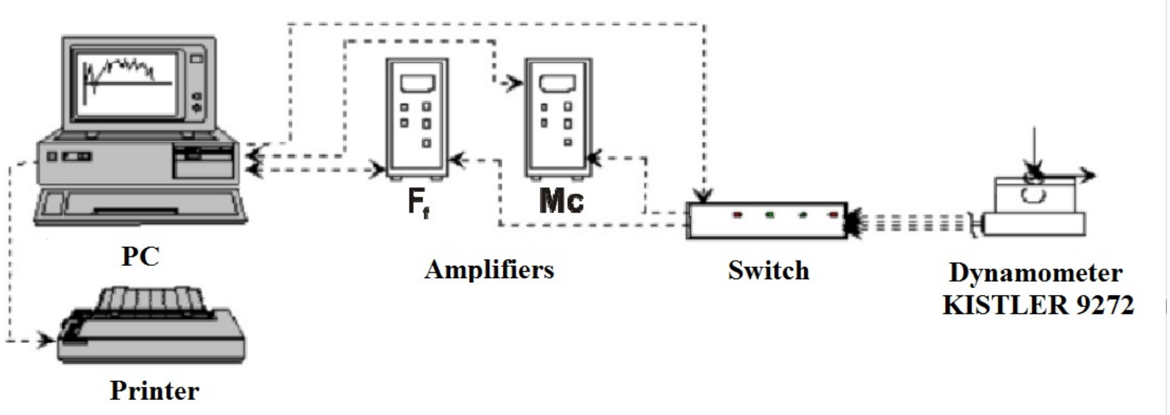


Fig. 37. Scheme of the experiment [20].

One forming tap was used for forming three threads with the same forming parameters, that are described above. Measuring of torque in all three predrilled holes was the main goal of the experiment.

Results and discussion of the experiment

As it was mentioned above, three holes drilled in previous operations were formed by one forming tap. Applying the scheme of the measurement in Fig. 37, data of torque was obtained. Then it was perfomed by charts in Fig. 38 for each hole.

The duration of each of the machining process was 15 seconds. Every chart was divided on intervals by points A-G. According to the machining process these intervals can be described for every chart generally as follow:

A-B: feeding the tool to the hole until it contacts with the workpiece;

B-C: beginning of the treatment, contact between the forming tap and the workpiece;

C-D: the forming process, during this period the tap undergoes through the workpiece's hole axially and when it's done the thread is formed;

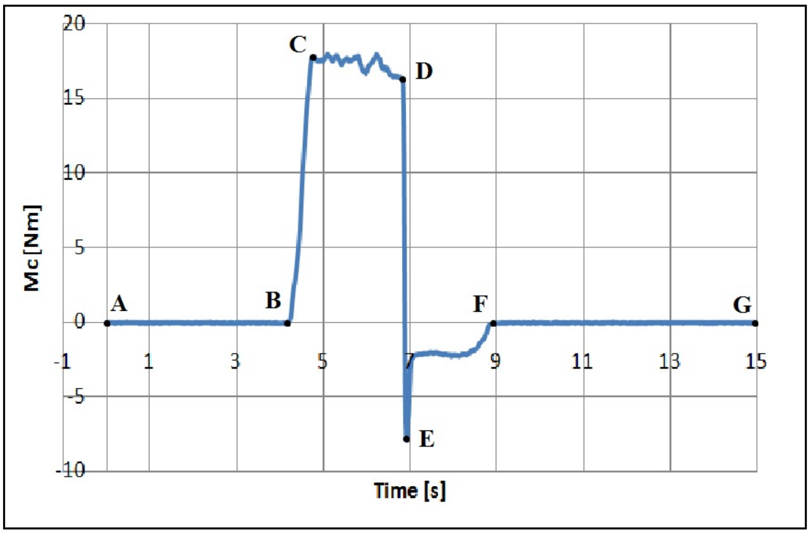
D-E: spindle reverse;

E-F: tool extracting from the thread;

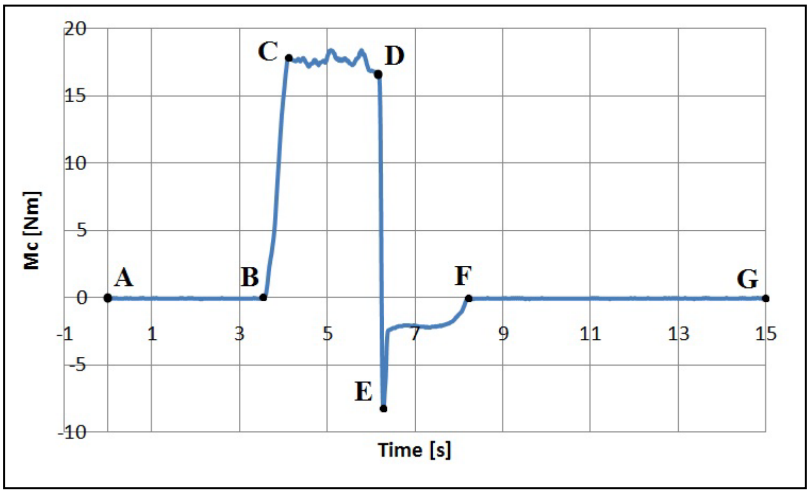
F-G: backward course of the tap.

The C-D interval is the most significant part of the experiment, because the thread is forming in this period. Theoretically, each C-D parts of every hole should be looked the same, because of unchangeable materials of the workpiece and the tap, machining parameters and lubricant, but experimentally obtained charts are different for every hole.

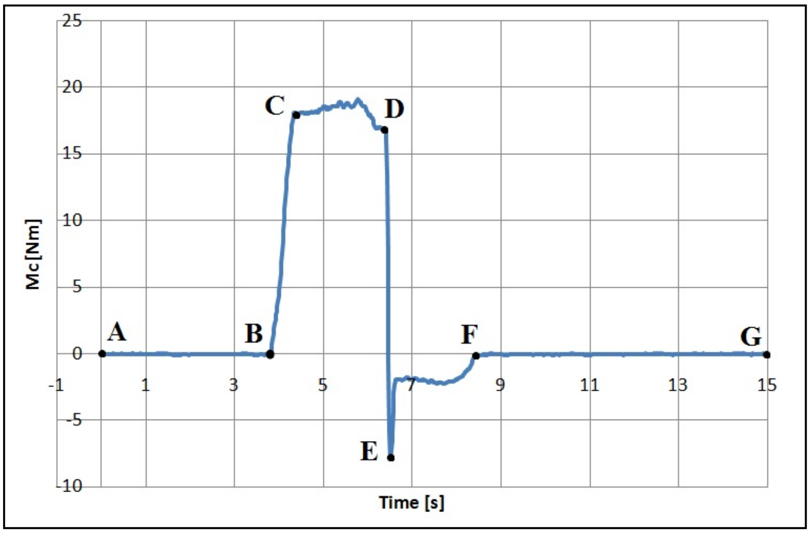
To find out what affects the values of the torque in C-D interval it is necessary to compare torque results.



a



b



c

Fig. 38. Torque charts, a) for hole n. 1 b) for hole n. 2 c) for hole n. 3.

In order to compare resulting torque data of each thread one-way ANOVA method can be applied.

An ANOVA test is a way to find out if survey or experiment results are significant. In other words, they help to figure out the necessity of rejection of the null hypothesis or accept the alternate hypothesis. Basically, groups are tested to see if there's a difference between them. Examples of when you might want to test different groups [34, 35]:

- A manufacturer has two different processes to make light bulbs. They want to know if one process is better than the other;
- Students from different colleges take the same exam. You want to see if one college outperforms the other.

One-way refers to the number of independent variables in analysis of variance test. One-way has one independent variable.

The hypothesis of the comparison may be formulated as follow: is there a dependence in torque's values dispersions between each measurement groups or dispersion is a result of the influence of external factors, i.e. caused accidentally.

The data were operated by using MS Excel 2007 and results are shown in Table 9.

Table 9. Results of one-way ANOVA test.

Group of values	Count of measurements	Standard deviation	Average value	Dispersion	P-value
Thread 1	126	0,359	17,467	0,129	6,269E-61
Thread 2	123	0,289	17,711	0,084	
Thread 3	125	0,398	18,342	0,158	

This test determines the level of significance of difference between dispersion of the groups. In this example, the dispersion analysis gives result of P-value less, then 0,05. It means that the dispersion within one group differs significantly from the other three dispersions. So, it can be supposed, that torque dispersion in C-D interval is a result of the influence of external factors.

It can be explained as follow: at each moment of thread forming process there were different structure of crystals in material and different amount of lubricant at the contact zone.

For the better estimation of torque dispersion the distribution histogram of torque in time interval C-D was evaluated, Fig. 39, Fig. 40 and Fig. 41.

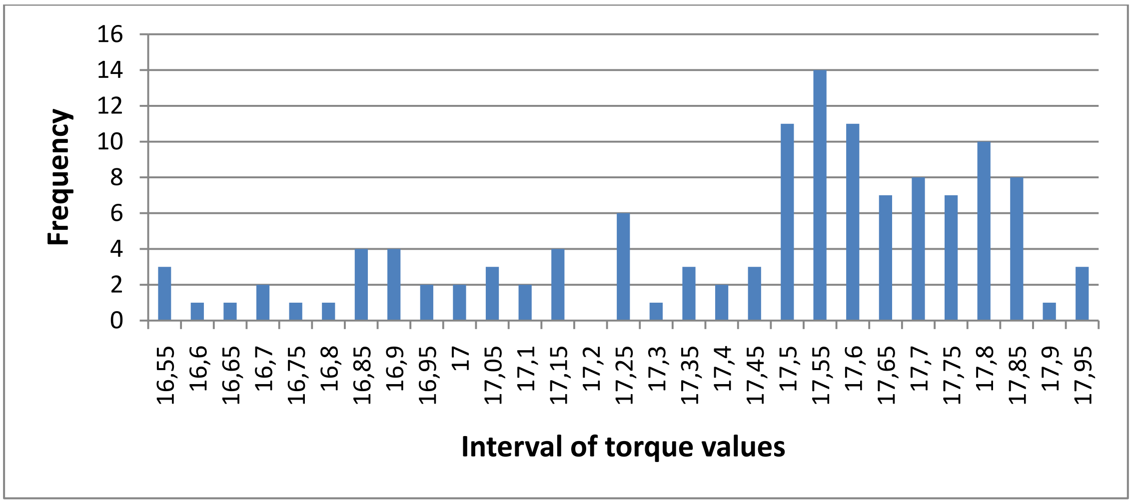


Fig. 39. Histogram of the first thread.

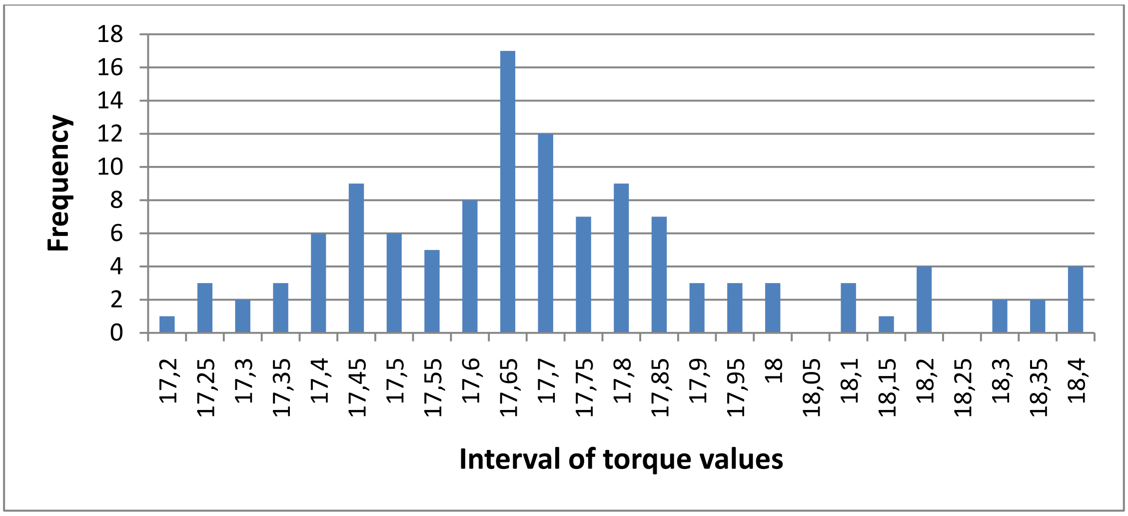


Fig. 40. Histogram of the second thread.

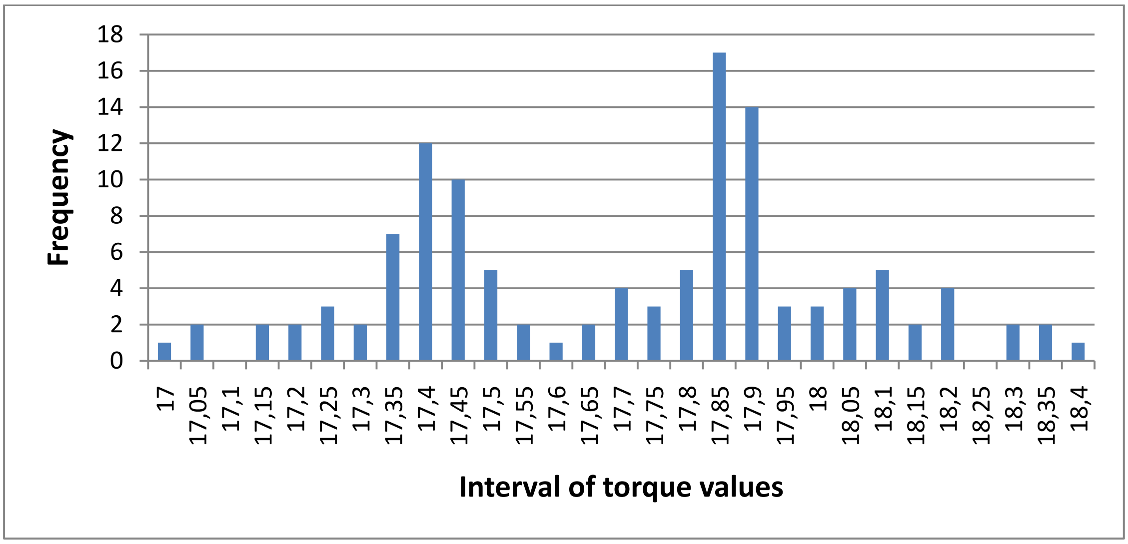


Fig. 41. Histogram of the third thread.

According to the distribution charts above, the torque distributions have deformation from normal distribution for each chart. It means, that there is no dependence between torque values in each distribution, and deviation of values was caused by occasion. The analysis, which was worked out in this work is incomplete, because three groups of measurements are not enough to compare torque values extensively and comprehensively.

6 EVALUATION OF ECONOMIC PARAMETERS

Production costs are all the expenses related to how a company operates and what it does in order get a product into the hands of a customer or client. Manufacturers are most concerned about with production costs because they deal with factors such as equipment, utilities, raw materials and labor. All these count as production expenses, but companies have found it best to divide them up into different categories for closer analysis - such as explicit and implicit costs or fixed and variable costs [33].

Fixed costs are costs that does not change with an increasing or decreasing in the amount of goods or services produced or sold. Fixed costs are expenses that have to be paid by a company, independent of any business activity. Fixed costs are usually used in breakeven analysis to determine pricing and the level of production and sales under which a company generates neither profit nor loss. Property taxes, insurance and administration's salaries, for example, are fixed costs.

Variable costs are corporate expenses that varies with production output. Variable costs are those costs that vary depending on a company's production volume; they rise as production increases and fall as production decreases. Variable costs includes energy, raw materials and equipment wear. Fixed costs and variable costs comprise total cost.

One of the main purpose in manufacturing is reducing of production costs together with increasing of efficiency. Direct costs for manufacturing one internal thread may be calculated as follow [20]:

$$N_D = N_M + N_R = t_{AS} \cdot \frac{N_{sn}}{60} + \frac{C + N_2}{Q_Z} = t_{AS} \cdot \frac{N_{sn}}{60} + \frac{C + t_{adj} \cdot \frac{N_{adj}}{60}}{Q_Z} \tag{31}$$

where: C	[CZK]	-	the tool price
N_D	[CZK]	-	direct costs for one thread manufacturing
N_M	[CZK]	-	machining costs
N_R	[CZK]	-	costs, connected with the tool replacement
N_{adj}	[CZK.hour^{-1}]	-	costs, connected with the time of tool adjustment
N_{sn}	[CZK]	-	costs of machine per one hour
N_2	[CZK]	-	costs of tool adjustment and mounting
Q_Z	[-]	-	the amount of manufactured threads
t_{AS}	[min]	-	time of machine's automatic operation
t_{adj}	[min]	-	time of tool adjustment and mounting

All the data, necessary for calculation are presented in Table 10.

Table 10. Specified parameters.

Parameters		Value
The tool price	C	430 CZK
Costs of machine per one hour	N_{sn}	870 CZK.hour^{-1}
Costs, connected with the time of tool adjustment	N_{adj}	205 CZK.hour^{-1}
The amount of manufactured threads	Q_Z	3
Time of machine's automatic operation	t_{AS}	0,25 min
Time of tool adjustment and mounting	t_{adj}	5 min

According to the technical information of Brno University of Technology researchs, the experimental forming tap is able to maintain the manufacture of at least 300 threads. Direct costs for manufacturing one internal thread by forming tap:

$$N_D = t_{AS} \cdot \frac{N_{sn}}{60} + \frac{C + t_{adj} \cdot \frac{N_{adj}}{60}}{Q_Z} = 0{,}25 \cdot \frac{870}{60} + \frac{430 + 5 \cdot \frac{205}{60}}{300} = 5{,}12 \text{ [CZK]}$$

The approximate theoretical price of one thread, manufactured by forming tap, was calculated.

CONCLUSION

Nowadays, theoretically and practically it is proved, that threaded connections will be applying for a long time, because it is relatively simple and inexpensive method of connection of interchangeable parts. Simple and affordable interchangeability is a distinguishing feature of the details of our time. Moreover, threaded connections are used in moving parts, when it is necessary to provide high accuracy of movement, as for example, in lathe machines, medical devices and measurement tools.

It was the first work of the author in the field of numerical processing of the data obtained during the tap forming tests. Three holes were machined by forming tap. The hypothesis was checked of the dependence of the torque deviations between each groups of torque measurements. It was estimated, that deviation of torque values was caused by different independent occasions, such as different structure of crystals in material being machined and different amount of lubricant at the contact zone.

It is necessary to proceed researchs in the field of thread manufacturing because of its widespread application and great demand in different significant for human being branches, such as medicine, civil or electrical engineering, that is important to reduce production costs and increase manufacture effectiveness.

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LIST OF USED SYMBOLS AND ABBREVIATIONS

Abbreviation	Description
BSW	British Standard Whitworth
CNC	Computer Numerical Control
ČSN	Česká Státní Norma
DIN	Deutsches Institut fur Normung
HSS	High Speed Steel
ISO	International Organization for Standardization

Symbol	Units	Description
C	[CZK]	The tool price
$\boldsymbol{D}$	[mm]	Major diameter of internal thread
$\boldsymbol{D_1}$	[mm]	Minor diameter of internal thread
$\boldsymbol{D_2}$	[mm]	Pitch diameter
$\boldsymbol{D_3}$	[mm]	Bottom diameter of internal thread
$\boldsymbol{EI}$	[mm]	The lower limit of tolerance for female thread
$\boldsymbol{ES}$	[mm]	The upper limit of tolerance for female thread
$\boldsymbol{F}$	[N]	The resultant tapping force
$\boldsymbol{F_{A,ij}}$	[N]	The axial cutting force
$\boldsymbol{F_C}$	[N]	The regular cutting force
$\boldsymbol{F_f}$	[N]	The frictional force
$\boldsymbol{F_I}$	[N]	The indentation force
$\boldsymbol{F_n}$	[N]	The normal force
$\boldsymbol{F_{R,ij}}$	[N]	The radial cutting force
$\boldsymbol{F_{T,ij}}$	[N]	The tangential cutting force
$\boldsymbol{F_{thr}}$	[N]	The resulting thrust force
$\boldsymbol{H}$	[mm]	Theoretical depth of the thread
$\boldsymbol{H_1}$	[mm]	Primary depth of internal thread
$\boldsymbol{H/x_1}$	[mm]	Innermost height of external thread
$\boldsymbol{H/x}$	[mm]	Outermost height of external thread

$\boldsymbol{M}$	[Nm]	The resulting torque
$\boldsymbol{N_2}$	[CZK]	Costs of tool adjustment and mounting
$\boldsymbol{N_{adj}}$	[CZK.hour^{-1}]	Costs, connected with the time of tool adjustment
$\boldsymbol{N_D}$	[CZK]	Direct costs for one thread manufacturing
$\boldsymbol{N_M}$	[CZK]	Machining costs
$\boldsymbol{N_R}$	[CZK]	Costs, connected with the tool replacement
$\boldsymbol{N_s}$	[rpm]	The spindle speed
$\boldsymbol{N_{sn}}$	[CZK]	Costs of machine per one hour
$\boldsymbol{P}$	[mm]	Pitch
$\boldsymbol{Q_Z}$	[-]	The amount of manufactured threads
$\boldsymbol{R}$	[mm]	Bottom radius of groove of internal thread
$\boldsymbol{S(i)}$	[mm.min^{-1}]	The surface speed of the *i*th tooth
$\boldsymbol{T}$	[min]	Spindle period
$\boldsymbol{T_1}$	[sec]	Time when the tap penetrates the workpiece
$\boldsymbol{T_2}$	[sec]	Time when all the tap's lobes are forming the material
$\boldsymbol{T_3}$	[sec]	Time when area of the surface contact isn't increase
$\boldsymbol{T_4}$	[sec]	Time when tap stops and travel out of the workpiece
$\boldsymbol{a_{e,ij}}$	[mm]	The radial distance between current cut and the previous one
$\boldsymbol{d}$	[mm]	Major diameter of external thread
$\boldsymbol{d_3}$	[mm]	Minor diameter of external thread
$\boldsymbol{e}$	[mm]	Innermost clearance of external thread
$\boldsymbol{ei}$	[mm]	The lower limit of tolerance for male thread
$\boldsymbol{es}$	[mm]	The upper limit of tolerance for male thread
$\boldsymbol{f}$	[mm]	Outermost clearance of external thread
$\boldsymbol{h(i)}$	[mm]	The depth of engagement of the *i*th tooth with the workpiece
$\boldsymbol{h_{ij}}$	[mm]	The instantaneous uncut chip thickness
$\boldsymbol{h_3}$	[mm]	Depth of the screw's thread
$\boldsymbol{l}$	[mm]	Screwing length
$\boldsymbol{r}$	[mm]	Bottom radius of groove of external thread
$\boldsymbol{r_{ij}}$	[mm]	The rotational radius

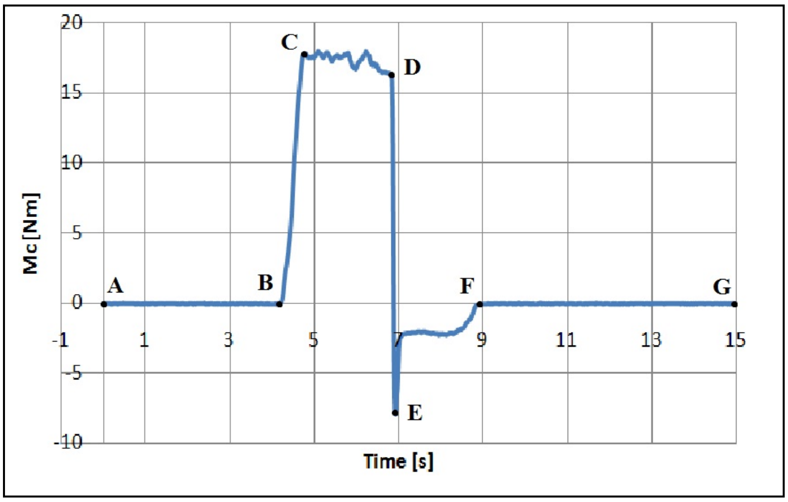
$\boldsymbol{t_{AS}}$	[min]	Time of machine’s automatic operation
$\boldsymbol{t_{adj}}$	[min]	Time of tool adjustment and mounting
$\boldsymbol{v_f}$	[$mm.min^{-1}$]	Feed velocity
$\boldsymbol{\alpha}$	[°]	Thread angle
$\boldsymbol{\delta}$	[mm]	Feed error
$\boldsymbol{\eta_l}$	[°]	The material flow angle

LIST OF ATTACHMENTS

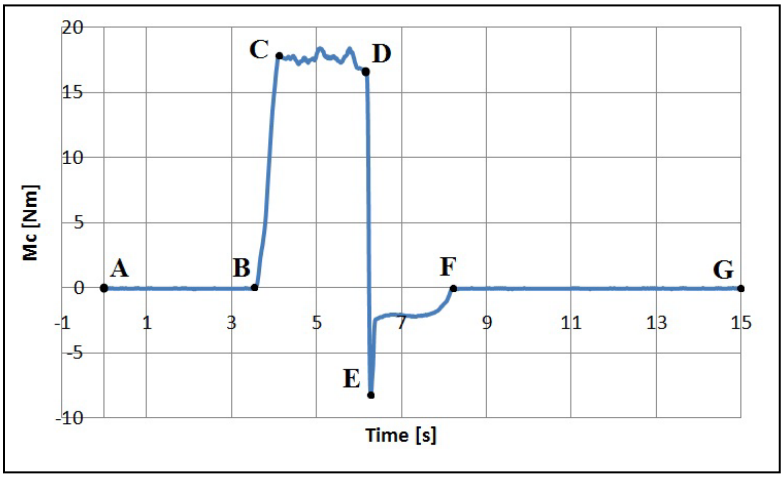
ATTACHMENT 1

```
N5    ZAV_REZ_M10_222
N10   T=ZAVITNIK_M10
N15   RYCHL X0 Y0
N20   RYCHL Z30
N25   RYCHL Z50
N30   RYCHL Y150
N35   M30
N40   END
```

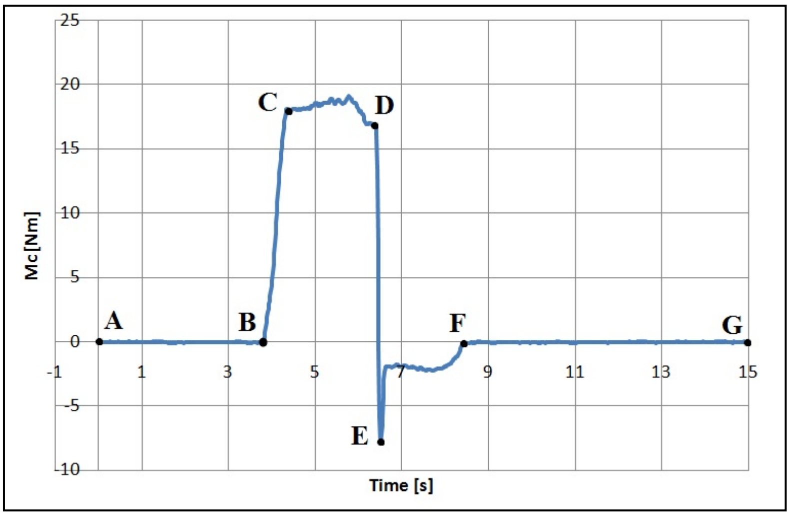
ATTACHMENT 2



a



b



c

Fig. 38. Torque charts, a) for hole n. 1 b) for hole n. 2 c) for hole n. 3.

ATTACHMENT 3

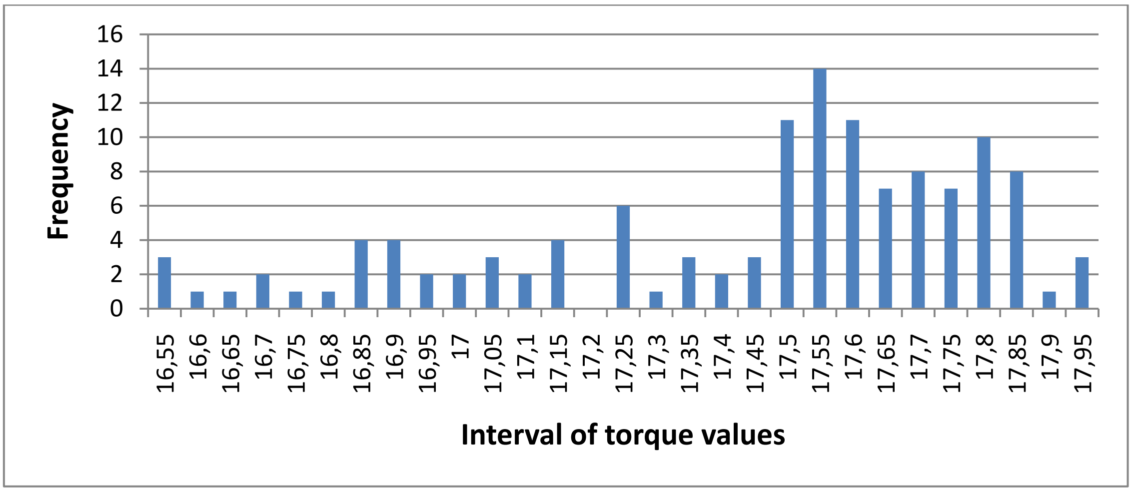


Fig. 39. Histogram of the first thread.

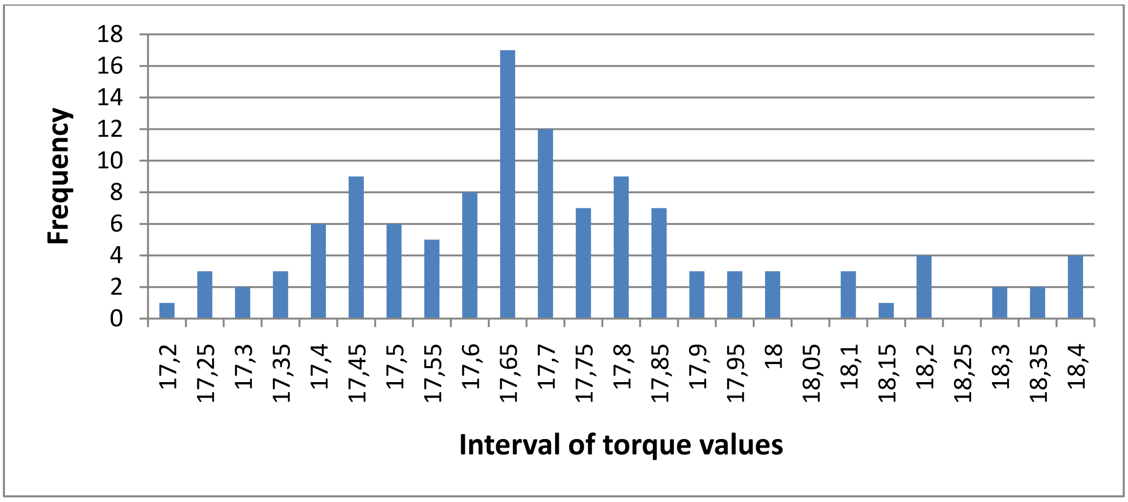


Fig. 40. Histogram of the second thread.

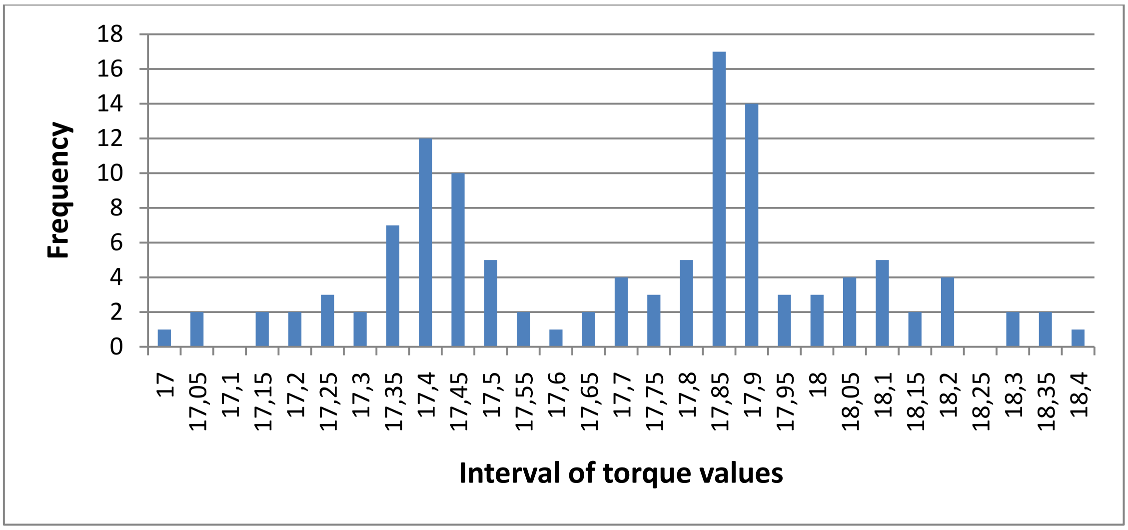


Fig. 41. Histogram of the third thread.